

# IOWA STATE UNIVERSITY

## Digital Repository

---

Retrospective Theses and Dissertations

Iowa State University Capstones, Theses and  
Dissertations

---

1969

## Preliminary design and feasibility study of a nuclear-powered agro-industrial complex in Iran

Ebrahim Jalali-Mossallam

*Iowa State University*

Follow this and additional works at: <https://lib.dr.iastate.edu/rtd>



Part of the [Nuclear Engineering Commons](#), and the [Oil, Gas, and Energy Commons](#)

---

### Recommended Citation

Jalali-Mossallam, Ebrahim, "Preliminary design and feasibility study of a nuclear-powered agro-industrial complex in Iran " (1969).  
*Retrospective Theses and Dissertations*. 4113.  
<https://lib.dr.iastate.edu/rtd/4113>

This Dissertation is brought to you for free and open access by the Iowa State University Capstones, Theses and Dissertations at Iowa State University Digital Repository. It has been accepted for inclusion in Retrospective Theses and Dissertations by an authorized administrator of Iowa State University Digital Repository. For more information, please contact [digirep@iastate.edu](mailto:digirep@iastate.edu).

70-13,593

JALALI-MOSSALLAM, Ebrahim, 1929-  
PRELIMINARY DESIGN AND FEASIBILITY STUDY OF  
A NUCLEAR-POWERED AGRO-INDUSTRIAL COMPLEX  
IN IRAN.

Iowa State University, Ph.D., 1969  
Engineering, nuclear

University Microfilms, Inc., Ann Arbor, Michigan

THIS DISSERTATION HAS BEEN MICROFILMED EXACTLY AS RECEIVED

PRELIMINARY DESIGN AND FEASIBILITY STUDY  
OF  
A NUCLEAR-POWERED AGRO-INDUSTRIAL COMPLEX IN IRAN

by

Ebrahim Jalali-Mossallam

A Dissertation Submitted to the  
Graduate Faculty in Partial Fulfillment of  
The Requirements for the Degree of  
DOCTOR OF PHILOSOPHY

Major Subject: Nuclear Engineering

Approved:

Signature was redacted for privacy.

In Charge of ~~Major Work~~

Signature was redacted for privacy.

Head of Major ~~Department~~

Signature was redacted for privacy.

~~Dean~~ of Graduate ~~College~~

Iowa State University  
Of Science and Technology  
Ames, Iowa

1969

## TABLE OF CONTENTS

	Page
I. INTRODUCTION	1
A. Why Desalination	7
B. Some Characteristics of South Coast of Iran	9
C. Locale Selection	11
II. CHOICE OF DESALTING PROCESS	14
A. Desalting Techniques	14
1. Multistage flash evaporator	17
2. The advantages of the MSF	21
3. Combined vertical-tube multistage flash evaporator (VTE-MSF)	21
4. Advantages of VTE over MSF	25
5. Auxiliary facilities	26
B. The Performance Characteristics of the Evaporator Plant	26
III. CHOICE OF THE ENERGY SOURCE	28
A. Nuclear Versus Fossil Fuel	28
B. Reactor Type Selection	30
IV. PRELIMINARY DESIGN OF NUCLEAR REACTOR	34
A. Design Criteria	34
B. Materials	36
C. Preliminary Core Design	37
1. Calculation of fuel load	37
2. Core design	40
3. Fuel design	42

	Page
D. Heat Transfer Consideration	42
1. Determination of heat transfer area	44
2. Determination of number of fuel rods and assemblies	44
3. Determination of coolant mass flowrate	44
E. Control and Safety Consideration	46
1. Introduction	46
2. Reactivity parameters and their effects	47
a. Steam coefficient of reactivity	47
b. Doppler coefficient	48
c. Temperature coefficient	48
d. Delayed neutron coefficient	49
3. Safety analysis	49
V. THE PRODUCTS OF THE COMPLEX	51
A. Introduction and Criteria	51
B. Estimation of Power and Steam Costs	53
C. Estimation of Water Cost	55
D. Industrial Products	58
E. Agricultural Products	64
VI. ECONOMIC ANALYSIS OF THE COMPLEX	70
A. Capital Costs	71
B. Annual Operating Costs	74
C. Income	77
VII. CONCLUSION	81
VIII. SUGGESTION FOR FURTHER INVESTIGATIONS	83

	Page
IX. REFERENCES	85
X. ACKNOWLEDGMENTS	90

## I. INTRODUCTION

World peace and progress cannot be maintained  
in a world half fed and half hungry.

J. F. Kennedy 1963

Iran is situated in the temperate zone between  $25^{\circ}$  and  $40^{\circ}$  north latitude and  $44^{\circ}$  and  $64^{\circ}$  east longitude and covers about 1.6 million square kilometers (628,060 square miles). It occupies the western half of the great Iranian plateau, being bounded by the Persian Gulf and the Gulf of Oman on the south and by the Caspian Sea on the north. Most of the land is desert and mountain. Mountains spread a gigantic V over the nation. Between the ranges lies a high plateau where streams disappear into desert sand. Only a strip along the Caspian Sea, nestling at the foot of rain-blocking peaks, gets water enough to bloom with subtropical growth. But the South coast region although fertile is arid.

The total population of Iran is almost 26 million, about 70% of which is agrarian. Agriculture is developed mainly along the Caspian Sea coast, Rezayeh Lake area, and in alluvial basins where water of good quality is available.

The water resources of Iran, apart from the saline water, decrease from the north to south and from the west to east.

Rivers which flow towards the Persian Gulf and Oman Sea are fresh at origin but because of close contact with gypsiferous and saliferous formations become saline and useless.

The provision of adequate amounts of suitable water for domestic and agricultural use has been a problem in Iran since the earliest recorded

time, and many of the techniques developed by the ancient Persian are still in use today. Over twenty-five thousand ghanats\* are still in use and produce some 12 million cubic meters of ground water per year or about two-thirds of the total (29).

Iran has the following worldwide general problems:

1. At the present, Iran produces less food than an adequate minimum diet requires. This condition may best be overcome by increased production rather than increased imports.
2. Doubling the population by the end of this century seems certain, even allowing for the most optimistic success with the birth control efforts.
3. With an improving standard of living, the per capita consumption of water will increase, both for agricultural and domestic uses.

The confidential publication of the Iranian Plan Organization on "Economical transformations of Iran and the general policy in the Fourth Development Plan" presents information to show that in order for the economical growth of Iran to be balanced and the Gross National Product to be increased to 6% after completion of the Fourth Development Plan in 1972, agricultural production must have increased 85% over 1965; mineral

---

\*The ghanat, or man-made underground channel, used for thousands of years in Iran, is one of the most remarkable systems of conveying water from its sources in the mountains to the plains using gravity as the driving force. The typical ghanat starts in the foothills where the "mother" well meets an aquifer with a sufficient amount of water and conducts the ground water for long distances, until it reaches the surface of low-lying land to be irrigated.



production must at the same time have a four or five fold increase; and industrial production must have an increase of 81.6%.

Despite the considerable expansion of water-production capabilities following the establishment of the Ministry of Water and Power, the main difficulty is in keeping pace with the needs of the people for assistance in the supply of additional water for expanding agricultural development. Not only are these needs increasing relative to the supply of water but they are also becoming broader and more complex.

Dams have been constructed to provide reservoirs for storage and subsequent distribution of water during the summer growing season. However, conflicts between users of surface water and groundwater are certain to result from the interference with the natural regime of the waterflow. The ghanat system, which is a natural drain depending upon a high water table for successful operation, is inefficient from the agricultural point of view because the production rates are greatest during the early summer when the needs are small, and least in late summer when the needs are great.

Several books could be written about food and water problems in Iran. This study will concentrate on the feasibility of a nuclear-powered agro-industrial complex\* for increasing food production in Iran.

The complete answer of even this question is not easy to provide. This entails team work with tens of people (Engineer, technologist, water

---

\*The complex considered in this study consists of a large, centrally managed farming area equipped for efficient water use, and a nuclear-powered desalination unit (Fig. 1.1.).

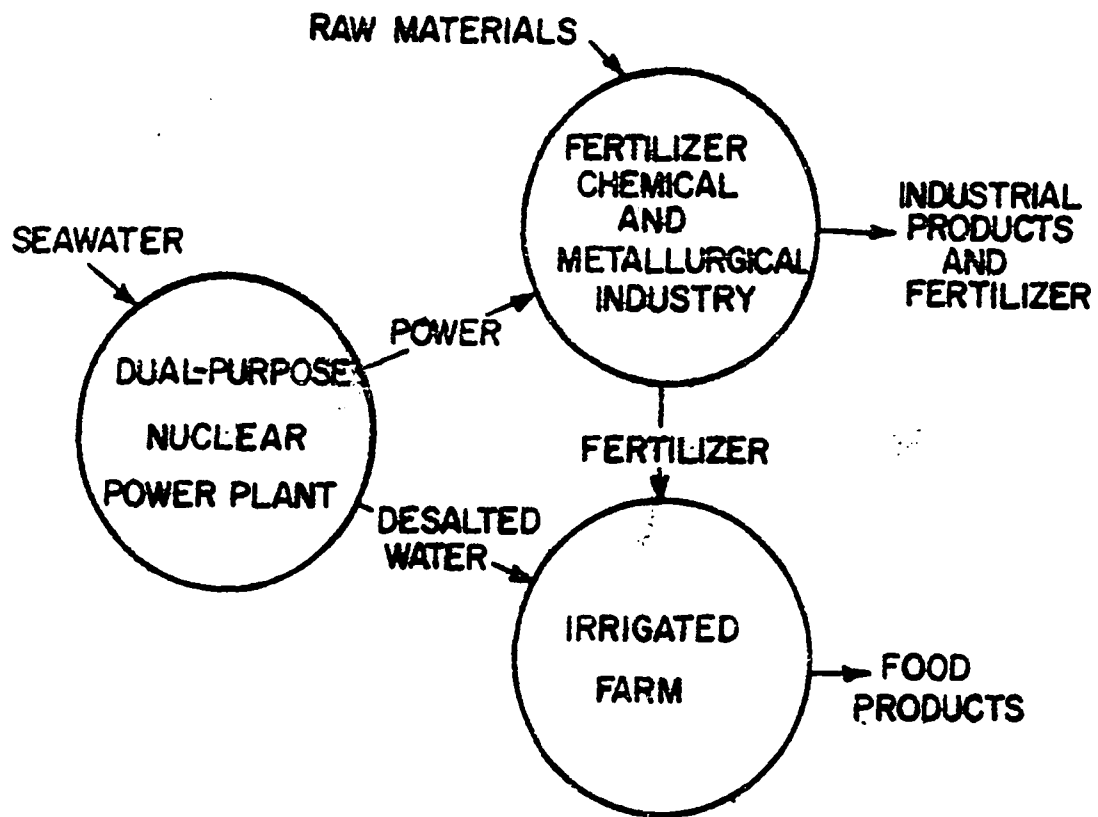


Fig. 1. 1. Agro-industrial complex

planner, sociologist, economist, agronomist, etc.) and several ministries and government organizations such as Ministry of Agriculture, Ministry of Economy, Ministry of Water and Power, Plan Organization, etc., involved in this study. A large computer program might become necessary to establish a technical and economic optimum.

The author would like to accomplish a preliminary feasibility study of the above-mentioned complex. In this study the permissible cost of desalted water will be viewed in the context of the cost of obtaining food at the South coast of Iran by other alternatives; the value approach as opposed to the cost per thousand gallons.

There is no doubt that agricultural use of water is greater than industrial or domestic use, and biological processes involved remove much of that water from immediate circulation. Therefore, the cost of this water must be kept as low as possible. Traditionally in developed countries agricultural water has been subsidized, that is, paid for by the home owner and industrial users through taxes and higher water rates. In Iran, however, as well as other developing countries seeking to increase their water resources--through mining and transport of underground water supplies, by building high dams to create reservoirs, or with desalination technology--ultimately will have to find a way of paying for the water which at the present time is mostly subsidized by the government.

The word "cost" causes confusion in the discussion of the desalination economy. It is very easy to put a price tag on the "cost" of desalinated water. It is, however, difficult to figure the "cost" to society of a village populated by children growing up half-fed amidst hectares of untilled land that is not farmed because there is no water with which to irrigate.

Vice Admiral Hyman G. Rickover said (33), "In my opinion the most damning thing you can say about cost effectiveness studies is that they don't--and the types of studies they make render it impossible to--take

account of human life. They do not believe that the good is as valuable as the profitable."

Admiral Rickover's condemnation of cost-effectiveness studies can be applied in the field of water supply.

Water is not the only product of a desalination plant. There are several other products or subproducts which are as important as the water itself. Improved health is one. Waterborne illness is one of the public-health problems in the southern region of Iran. People whose health is good do not remain burdens on the economy. They become boosters.

More water means more food, national health, productivity, and income. But what the author is concerned with, in this study, is the profit itself, regardless of any other consideration discussed before. That is, is the rate of return\* of the complex comparable to that of the other firms, regardless of government subsidy, fishery improvement or humanistic consideration?

The internal rate of return could be increased by bringing an extensive area under cultivation with aid of well-experienced experts by applying the most advanced irrigation technique and using mechanical equipment and chemical fertilizers. Application of a rather high level of technology involves an efficient water-management system, the adequate availability of educated and skilled manpower to handle the numerous

---

\*The internal rate of return may be considered as the interest rate at which a project will break even in the sense that the income from the investment equals all costs including return (at that interest rate) on investment.

problems and projects on the water supply side, as well as adequately educated water users. Illiterate farmers cannot easily gain an understanding of modern water technology. The author, therefore, is in favor of the complex as opposed to a desalination plant and selling the desalted water to farmers. In this complex highly efficient and controllable irrigation should be used, along with optimum amounts of fertilizer at the right time in the growth cycle.

A central laboratory would analyze the soil from each block of land and determine the appropriate fertilizer mix. Pests also should be controlled. Irrigation would be monitored by moisture tests.

#### A. Why Desalination

There are several methods to produce food, but there is one main problem to all of these methods--and that is time. It takes time to develop new agricultural techniques, to educate illiterate farmers, and to develop new strains of high-yield crops which can withstand the fungus, insects, and other problems of agriculture in a developing country like Iran. Bringing the arid coast land into production using desalted water from the ocean, which could be accomplished in a relatively less time, is the most promising method.

Other advantages of desalination are as follows:

1. Desalination makes possible the gradual expansion of a supply system on the basis of step-by-step (modular-design approach) installation of plant capacity, whereas other alternatives may require construction of a costly reservoir or pipeline with a large capital investment

in capacity perhaps not used for a decade (decades)\*,

2. Desalination provides a quick supply of fresh water when it must be acquired immediately,

3. The technology of desalination, as well as that of nuclear, is improving which will result in a decrease in the desalting cost, where the conventional water supply costs will increase simultaneously,

4. Mineral by-products are available from the water processing in a desalination plant.

To show how modern technology can increase the internal rate of return, some hopeful views of the potential of desalination in providing food for mankind taken by R. Philip Hammond, Director of the Nuclear Desalination Program at the Oak Ridge National Laboratory of the U. S. Atomic Energy Commission will be given here.

Speaking at the symposium "Water Production Using Nuclear Energy" at the University of Arizona in early 1966, Hammond reviewed the basic elements of the problem. Crop utilization of water, he told the Arizona conference, must be high to minimize the consumption of desalted water. He noted that the Agricultural Research Service has shown that over 5,000 pounds of wheat and corn can be grown per acre-foot of water used, and that that yield of these proportions should be readily transferable to

---

\*By building such a plant in a series of separate units, or modules, which are joined together, water supply planners can begin producing fresh water without waiting for the entire construction to be completed, and can add additional modules if water needs increase, without having to redesign and rebuild the entire plant.

irrigation of arid land with distilled water. He compared that figure with present average yield of 1,200 pounds per acre-foot, and he pointed out that such an increase would be equivalent to a 75% cut in the cost of water.

Looking ahead, he dared hope that the cost of fresh water produced by the Metropolitan Water District Plant in southern California would halved in fifteen years by continued improvement in both nuclear reactor and desalination plant technology, and that genetic improvements in grain seeds would also increase the probable yield twofold in the same period, so that eventually it might cost as little as 1 cent a day to produce the food needed by a single person. "Such cost," he said, "would appear to fall in the range which could make a desert green and give desalination a major role in man's future food supply."

Iran must look for a method which gives a good result within ten years. In the author's opinion, the best, or at least the most promising solution to the food problem in Iran is bringing some of the fertile arid land of the South coast into production using desalted water from the Persian Gulf and/or the Gulf of Oman.

#### B. Some Characteristics of South Coast of Iran

Due to its geological position the coastal areas of Persian Gulf and Gulf of Oman is hot\* and humid in summer and mild in winter, but with low rainfall. The annual precipitation average is normally between 57

---

\*In the summertime, the temperatures reach 50° C (120° F) in some areas.

and 205 mm.\*

This area consists of coastal lowlands, composed of fine-grained deltaic sediments, and the foothills consist of Meocene (29).

In addition to the general paucity of rainfall and resultant lack of available water, there is a serious difficulty as a result of the contamination of water resources from the dissolution of soluble evaporitic sediments and the high evaporation rate in inland basins. Deposits of limestone, gypsum and rock salt in Upper Meocene sediments cover relatively large areas along the Persian Gulf (29). In these areas, even where water is available, it is apt to be too saline for economic agricultural use. Prevention of this deterioration of water resources is a problem of grave concern to the government. Salt diapirs, common in the southern coast, are especially harmful because they are composed largely of high soluble salts which may effect a very large area despite the fact that they cover only small areas themselves. The total area in this region which is flat enough to be cultivated is estimated to be between 250 to 300 thousand hectares.\*\* This low land strip along the Gulfs is from 2 to 6.5 miles wide and some areas like Bandar Abbas area or the area near the border of Pakistan reaches up to 30 miles wide.

The average population density according to the latest census (Nov. 1966) on the southeastern coast is about three persons per square

---

\*Akhavi, M. Water Resources, Iowa State University, Ames, Iowa. Private communication. 1969.

\*\*Ferdows, K., Tehran, Iran. Plan organization. Private communication. 1969.



kilometer (1) (8 per square mile).

The cultivation of the South coast of Iran has the following advantages:

1. The presently available crop varieties and farming techniques of the U. S. arid West can probably be used,
2. The land has a year-round growing season so that the investment in water supply, water distribution, sprinklers, etc., can be used at high load factor,
3. The availability of fish and shellfish as an ever present source of food is another advantage of this area as is the advantage of any coastal deserts. Desalination can make the building of new or enlargement of the fish processing.\*
4. This lowly populated region can attract capital, provide jobs, produce food, and help reduce population pressure in other areas, especially in Tehran.\*\*

A map of the South coast of Iran is shown on page 12.

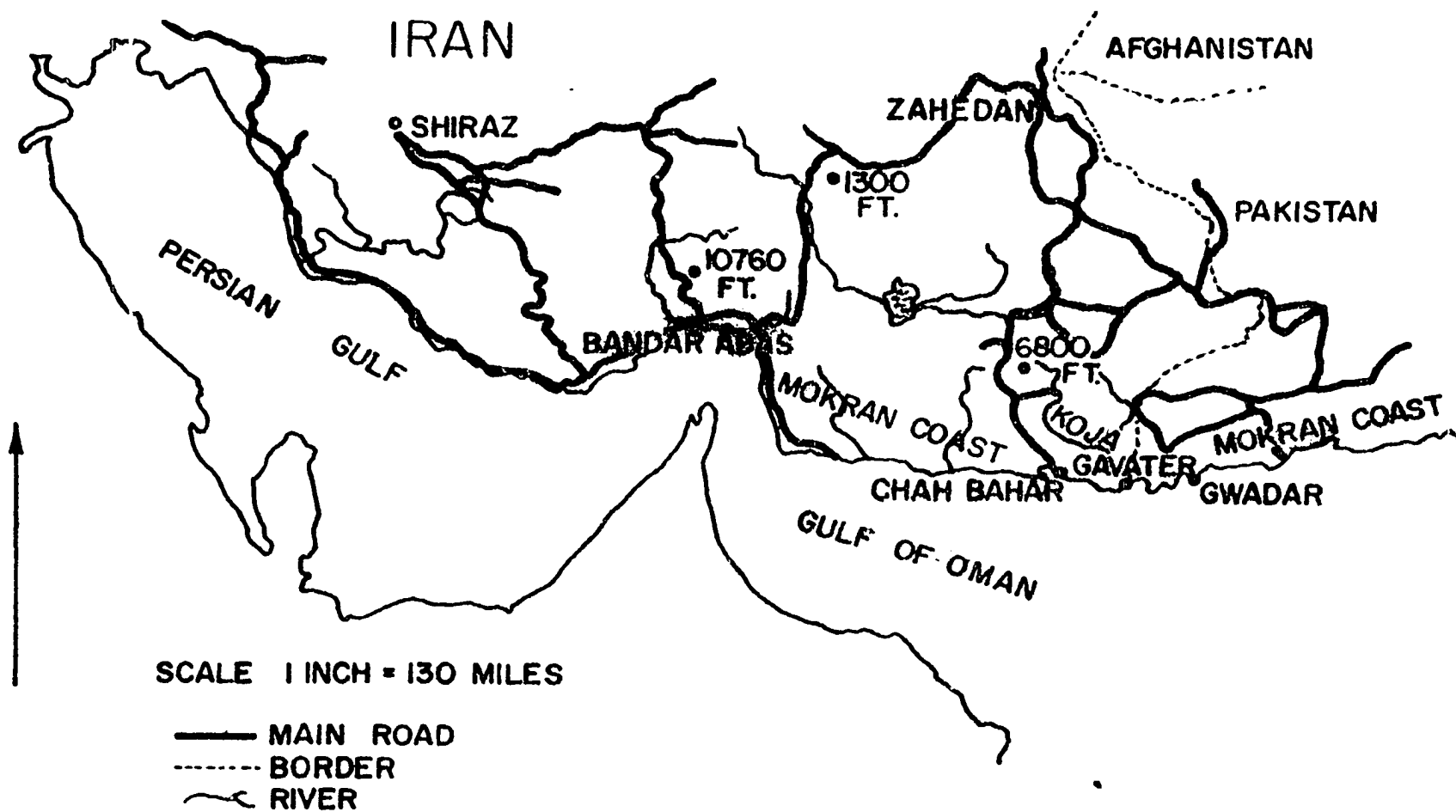
### C. Locale Selection

In selecting possible areas for potential application of the agro-industrial complex, many factors had to be considered. Since the only arid and semi-arid areas near the sea in Iran are along the South coast the complex should be located somewhere on this coast. The exact location

---

\*Peeveril Meigs (31) believes that the processed fish products are valuable enough to support the cost of desalination.

\*\*Tehran, the capital city of Iran, has about 1/10 of the population of the whole country.



Map 1. South Coast of Iran

could be determined after careful studies of a group of people expert in different fields by considering the agricultural, industrial, social and political factors.

The author's first choice is somewhere in the Mokran Coast of Iran and Pakistan, on or near the border of these two countries.

Iran and its good neighbor to the southeast, Pakistan, share much in common, including the great areas which are very short of water. Together and/or with the help of some international organizations such as the International Atomic Energy Agency, they would explore a promising answer to a very difficult but a natural problem. The main advantage of this joint project is that the capacity of the complex could be quite large and, thus more economical.

Mokran Coast of west Pakistan is extremely dry. It stretches for 640 kilometers along the Gulf of Oman, and covers terrain between Karachi and the Iranian border. The scattered fishing villages along the coast are in constant need of fresh water. Because the villages make a substantial contribution to Pakistan's foreign exchange, the government is anxious to provide them with a source of fresh water. The water from a handful of springs and wells in the area of Gwadar, a community of about 8,000 people near the Iranian border, sells for \$25 per 1000 gallons, and in the time of scarcity for \$50 (33).

An alternative location is anywhere in the central or eastern part of the South coast. For example, Bandar-Abbas, which is the largest town in this region, has harbor facilities and an international airport.

## II. Choice of Desalting Process

Essentially there are three types of choices to be made in the selection of desalting processes:

- (a) method of desalting
- (b) size of the plant
- (c) type of the fuel to be used (fossil or nuclear)

Actually all of these choices are interdependent. They also are conditioned by such matters as the size of prospective markets (or need) for water and power, the cost of fuel, safety requirements, etc.

In this chapter parts (a) and (b) will be discussed. The type of fuel will be selected in chapter III.

### A. Desalting Techniques

Providing the source of adequate, low cost energy is only one part of the desalting problem. The basic question is how most efficiently and economically to convert saline water to fresh.

The ideal desalting process would require low-energy input, have low capital cost, and low-cost operation and maintenance. Not all these attributes are present simultaneously in any process based on today's technology. But some existing techniques are promising for particular degrees of water salinity and amounts of water required.

The processes which can be used for the desalination of saline water fall generally into two basic classifications. First are those that take the fresh water away and leave a concentrated brine behind, such as evaporation and reverse osmosis. Processes in these groups are mostly

applicable to sea water. In the second group are those that remove salt and leave fresh water behind, such as electrodialysis and ion exchange. The process that has been developed to the point of actual use are shown in Table 2.I.

Table 2.I. Classification of saline water conversion processes

---

A. Processes that separate water from the solution

1. Distillation or evaporation
  - a. Multiple-effect long-tube vertical
  - b. Multistage flash
  - c. Vapor compression
  - d. Humidification (solar)
2. Crystallization or freezing
  - a. Direct freezing
  - b. Indirect freezing
  - c. Hydrates
3. Reverse osmosis
4. Solvent extraction

B. Processes that separate salt from the solution

1. Electrodialysis
2. Osmionisis
3. Adsorbtion
4. Liquid extraction
5. Ion exchange
6. Controlled diffusion
7. Biological system

The separation of water or salt from saline water requires energy and the second law of thermodynamics provides a basis for the calculation of the absolute minimum energy required by any desalination process. Since after evaporation recondensation takes place, heat then is recovered, and the only energy spent is the energy required for the compression of the vapor.

For seawater the theoretical energy required amounts to about 2.8 kw-hr/1000 gal of product at 77° F (40). This is the minimum energy required for an infinitely slow operation with no loss of any kind. Every practical process, however, requires much more than the minimum figure.

The energy requirements for six current conversion processes are listed in Table 2. II. (40, 52). It is estimated that, by the year 1980, research and development will have reduced the energy requirement of certain processes (40).

This table shows that those systems utilizing relatively low quality heat energy are the ones which have the highest specific energy requirements, while those with the lower specific energy requirements need high quality electrical energy.

There seems to be a general agreement among experts that water supplies in quantities above one million gallons per day are best served by evaporation (4, 33, 34, 50). The two main types of evaporator design are multistage flash (MSF) and vertical tube evaporator (VTE).

Table 2. II. Basic heat energy requirements for six saline water conversion processes

	Energy requirement (per gallon of product water)			
	1964 technology		Estimated for 1980 technology <sup>a</sup>	
	Btu	w-hr	Btu	w-hr
Processes using heat				
Multistage flash distillation	1020	300	610	180
Vertical tube evaporator	1020	300	610	180
Processes using electricity <sup>b</sup>				
Vapor compression distillation	610	60	360	35
Freezing	610	60	360	35
Reverse osmosis	510	50	310	30
Electrodialysis (for brackish water only)	250	25	150	15

<sup>a</sup>The estimated 1980 energy requirements are for the high-efficiency processes and are not applicable to processes using low cost energy.

<sup>b</sup>The energy values given for the "electrical" processes are thermal energies for the appropriate electrical power generation at 33% plant efficiency.

### 1. Multistage flash evaporator

All of the studies for proposed large scale plants now underway involve the employment of the multistage flash process. This process will be discussed briefly here. The term "flash" derives from the fact that part of a volume of hot water will change into vapor almost instantaneously

when it is admitted from one chamber into another in which there is a lower pressure and temperature.

The multistage flash evaporator concept is shown schematically in Fig. 2. 1. Seawater is first heated under sufficient pressure to prevent boiling in a section called brine heater. The brine heater is a shell-and-tube heat exchanger. When the heated brine leaves the brine heater, it is forced through an orifice into the first flash chamber (stage) of a multistage evaporator. Here the pressure is dropped slightly until boiling begins. A small portion of the water is vaporized (flashed). Condensation of the vapor on the tube at a lower temperature maintains the necessary pressure drop in the flash chamber. The vapor, free of the dissolved salts, flows to a heat exchanger and is condensed by the incoming seawater, which in turn becomes heated. Both the fresh distilled water stream and the more concentrated and somewhat cooler salt water flow separately to the second stage. Here, both streams begin boiling (because of lower pressure), with a small fraction of each stream changing to vapor, which is again condensed by the cooler incoming seawater stream. This process is repeated in many subsequent stages, where the pressure and temperature are gradually lowered with an economical approach to the inlet seawater temperature is reached. The amount of heat reused is optimized by a balance between the cost of additional heat transfer surface and the cost of the heat saved.

A measure of effectiveness of a given distillation plant in producing fresh water from seawater is given by the performance ratio. This ratio represents the number of pounds of product water produced by the plant



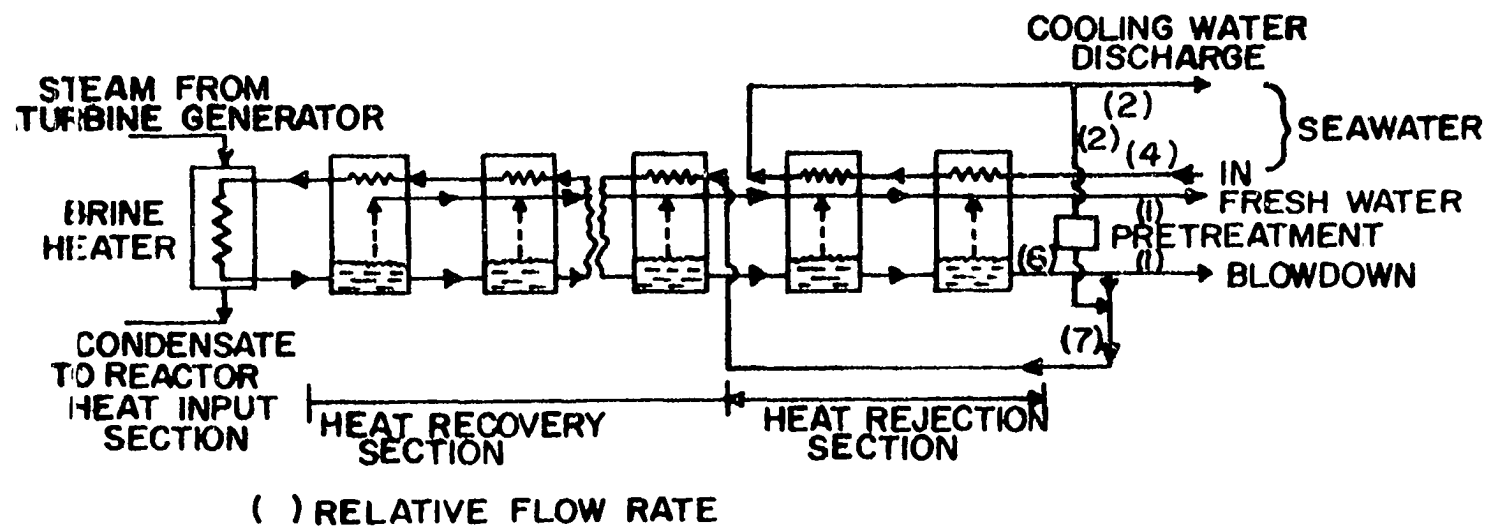


Fig. 2. 1. Flow diagram of multistage flash evaporator

for each 1000 Btu's of energy input to the seawater, or the pound of product water produced per pound of steam supplied to the plant. In MSF the performance ratio may exceed by about 12 (50).

Actually the seawater is progressively heated before being admitted to the brine heater. The progressive heating of the seawater feed is accomplished by piping the incoming seawater through the flash chambers, starting at the low temperature end.

Since the fraction of fresh water boiled off per pass through the evaporator is relatively small, a large recycle flow of the brine is generally required to reduce the amount of seawater to be chemically treated. In addition to the added pumping power required, the recycle flow causes a higher solid concentration (relative to the once-through system) in the brine which is in contact with the heating surface, so that careful attention must be given to the seawater chemical treatment method required to prevent scale formation. The scale precipitates which are deposited on the heat transfer surfaces and act as thermal insulators and reduce the efficiency of the evaporating process.

A closed-cycle process is proposed by R. E. Blanco et al. (5) for removing scale-forming elements from seawater (descaling). In this process all chemicals required for desalting are produced at the plant site, either directly from seawater or from recycle streams. An economic evaluation of desalting for the production of the 250 million and 1 billion gallon per day of fresh water is accomplished. In the latter case the desalting service could be provided for a fee of 1¢/1000 gal., which is competitive with the use of sulfuric acid for scale control. Credit is taken for the sale of hydrogen and chlorine.

The presence of excess oxygen and carbon dioxide in the brine causes increased corrosion of the evaporator tubes and decreases the useful life of the evaporator plant. Removal of this material is thus highly desirable and is accomplished in the deaerator.

## 2. The advantages of the MSF

In a study made for the Edison Electric Institute (11) it was stated that MSF is a superior process for these reasons:

a) Problems with the scale formation are minimized since there is no area of contact between the evaporating brine and metallic heat transfer surfaces,

b) The heated brine can be recycled, thereby reducing thermal energy losses and feed water treatment costs,

c) Multistage flash permits the widest range of operating temperatures,

d) High heat transfer rate, by using surfaces of minimum cost.

e) Adaptability to large size plant constructed of relatively inexpensive materials.

## 3. Combined vertical-tube multistage flash evaporator (VTE-MSF)

Experimental work for the Office of Saline Water of the United States Department of the Interior has demonstrated that vertical evaporator tubes with double-fluted surfaces can give heat transfer performance of 2 to 3 times higher than those attainable with smooth evaporator tubes (47, 50). This improvement in heat transfer allows a reduction in the quantity of vertical tubing and this, in turn, gives a corresponding reduction in the size of the structure needed for the production of a specified amount

of water.

The reference plant process is a forward-feed, 15 stages, falling-film vertical tube evaporator and a 50-stage flash evaporator for feed heating as shown in Fig. 2. 2. The plant performance ratio is 13 pounds of product water per 1000 Btu of heat. Seventy-five percent of the product water is produced in the vertical tubes and 25% in the feed-heater section.

About half the incoming seawater serves as coolant and is returned to sea after passing through condensers. The remainder is acidified with sulfuric acid to prevent scale from forming in the plant and deaerated to remove all dissolved gases. The cold treated seawater is then pumped through the continuous condenser tubes of the 50 flash evaporator stages. In each evaporator stage, vapor from boiling seawater condenses on the tubes through which cold seawater is flowing. In condensing, the vapor gives its heat to the seawater in the condenser tubes.

After passing from stage 50 through 1, the seawater inside the condenser tubes continues through a brine heater, where steam from the power plant (turbogenerator) heats the seawater to a higher temperature ( $260^{\circ}$  F). The hot seawater leaves the tubes and flows through the flash evaporator stages in an open stream on the floor, passing from stage to stage through orifices which provides progressively lower pressures in the stages from 1 through 50. As it enters each new stage, part of the hot seawater steam flashes into vapor, which is drawn through entrainment separator screens to condense on the cooler condenser tubes. A portion of the brine flowing through the flash evaporator is pumped from selected stages up into the vertical tube which are at the same temperature as the selected

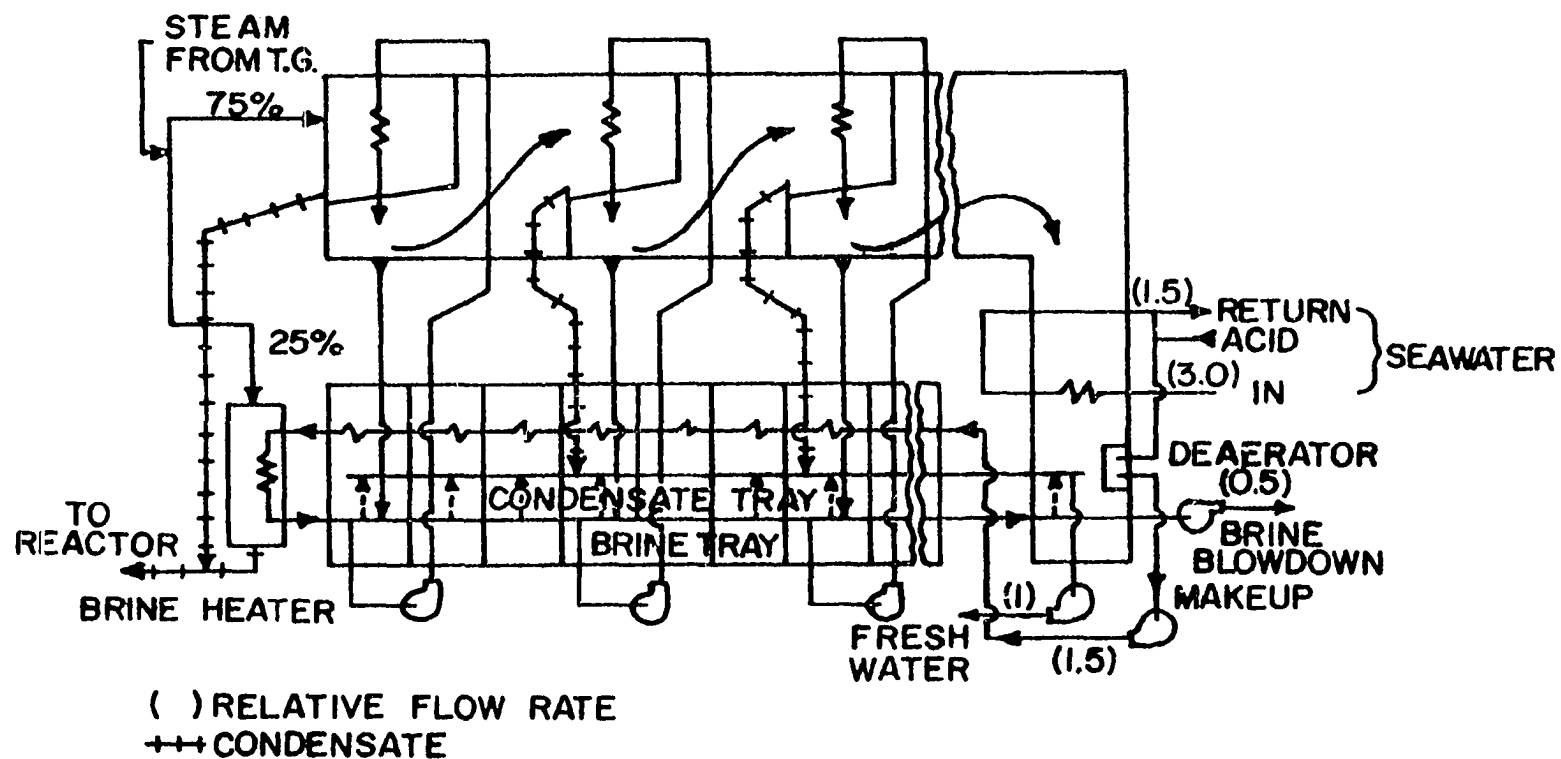


Fig. 2. 2. Schematic flow diagram of VTE plant

stages. There are three or four flash stages for each vertical-tube stage. A portion of this feed is evaporated as it flows downward through the vertical tube. Brine from the bottom of the vertical tubes flows back into the flash stage from which it was pumped. About 75% of the steam from the power plant condenses on the outside surface of the first vertical tube stage and the condensate returns to the power plant. The vapor generated in the vertical-tubes stage passes out, through an entrainment separator, and is used as the heat source for the succeeding vertical-tube stage, which is at a lower pressure, so that the brine in this effect boils at the slightly lower temperature. This process is repeated in 15 subsequent stages. The vapor from stage 15 is condensed in the final condenser, and the heat is rejected to sea.

The remaining 25% of the input heat (steam from the power plant) is used to provide the heat for final stage of seawater preheater (brine heater, Fig. 2. 2.). The initial seawater preheating is carried out in the MSF evaporator. The MSF section produces about 20% of the product water.

The VTE design makes possible a once-through seawater flow circuit, thus eliminating brine recycling. This reduces the problem of scale formation and thus allows a higher maximum brine temperature and brine effluent concentration, as well as giving a lower pumping requirement (about one-half)(50), than for the MSF design.

The plant contains several parallel and independent trains. Each train has 50 flash evaporator stages on the lower floor and 15 vertical-tube stages on the upper floor. To accommodate the increasing vapor flow area required with decreasing pressure, each train is trapezoidal in plan view.

The combination of vertical-tube evaporator with fluted tubes and a MSF preheater as described is a relatively new concept. However, vertical-tube evaporators using smooth tubes have been in operation for many years in different industries (salt, paper and chemicals); 1-Mgd seawater desalination plant built by the Office of Saline Water at the Freeport, Texas, began operation in 1961. There is no reason that the combination of two types of evaporators, which both have been used successfully for many years, would fail. The current experimental program in Oak Ridge National Laboratory (U. S. AEC), together with detailed design analysis, is quite encouraging (47, 50).

#### 4. Advantages of VTE over MSF

The advantages of VTE can be summarized as follows:

a) Problems with scale formation are nonexistent in a VTE plant operating on normal seawater and observing the same maximum brine temperature as the 250° F commonly specified for MSF. Scale-free operation at 265° F maximum brine temperature has been demonstrated over a 55-day continuous operation of the Freeport VTE plant (34). The actual advantage lies in the once-through seawater flow circuit, thus eliminating the brine recycling required in MSF,

b) Thermal energy losses and chemical treating costs are less for VTE processes, because brine effluent concentration ratio is 2.5 as opposed to the MSF concentration of 2. Thus, there is considerably less water to treat chemically and less hot brine to blowdown to waste. In addition the pumping energy requirement for VTE is about 50% of that required for MSF (34),

c) The evaporating heat transfer coefficients achieved in the smooth surface VTE are approximately 10 to 20% higher than for the MSF evaporators. The double-fluted tube exhibits an improvement in overall heat transfer by a factor of 2 or 3 compared with the smooth tubes (50),

d) For a given plant capacity the cost of the VTE is less than the MSF evaporator. This is the direct result of the above-mentioned advantages,

e) The land required for the VTE plant is much less than that required for a comparable MSF plant. Additional economic advantages are attributed to the inherent thermodynamic efficiency of the combined VTE-MSF process, and to the use of on-site sulfuric acid plant to supply acid for feed treatment (47).

## 5. Auxiliary facilities

Both types of evaporators require auxiliary facilities as follows:

- a) Seawater intake and return,
- b) Seawater chemical treatment plant for scale control,
- c) Deaerator,
- d) Product water treatment,
- e) Evaporator brine and seawater pumping.

The amount of pumping power required for two evaporators is 0.345 and 0.142 Mwe/Mgd for MSF and VTE respectively (50).

### B. The Performance Characteristics of the Evaporator Plant

The energy input to evaporator plant is provided by the condensation of the turbine-generator exhaust steam in the brine heater. The steam temperature and pressure at the brine heater are 260° F, and 35 psi



respectively. Considering this steam yields energy at a rate of about 938 Btu per pound, for the production of 500 Mgd water and with the plant performance ratio of 12 pound per 1000 Btu, the flow rate at the brine heater should be

$$(500 \times 10^6 \text{ gal/day}) (8.35 \text{ lb/gal}) (\text{day}/24 \text{ hr}) (\text{lb}/938 \text{ Btu})$$

$$(1000 \text{ Btu}/12 \text{ lb}) = 1.54 \times 10^7 \text{ lb/hr.}$$

The performance characteristics of the plant considered here can be summarized as follows:

Product water capacity	500 Mgd
Performance ratio	12 lb/1000 Btu
Maximum brine temperature	260° F
Water quality	23 ppm
Lifetime	30 years

### III. CHOICE OF THE ENERGY SOURCE

#### A. Nuclear Versus Fossil Fuel

The main question is what source of energy should be used. The major sources of energy are gas, oil, coal and nuclear fuel. The cost of steam is the primary factor in considering whether the source of heat should be from fossil or nuclear fuels. Desalination plants require large amounts of steam energy to heat the seawater under the pressure to about 260<sup>0</sup> F. The desalination process also uses a considerable amount of electrical energy to operate the pumps bringing in the seawater as well as the pumping required for collecting and conveyance of product waters.

The utilization of nuclear fuel is part of mankind's overall long-term effort to conserve his natural resources. There is a need not only to conserve but also to develop and more efficiently utilize all energy sources in Iran, as well as in any other country. It is the author's duty to try to help to bring the benefits of nuclear energy to his country.

There is not enough information about the coal reserves in Iran, however, there does not seem to be a shortage of coal which could be used in power plants\* for a few decades. Although the petroleum and natural gas resources are extensive, future generations will need our fossil resources as much if not more than we do. Demands of energy are increasing much faster in a developing country like Iran than in an already developed country.

What are the fossil fuel reserves in Iran? How long will they last?

---

\*The government of Iran had a little problem to find high quality coal (which could be converted to coke) for the new steel mill.

Answers to these questions depend upon whose estimates are used and what assumptions are made. In 1963 the oil resources of Iran were estimated to be about 55 billion tons. Considering the amount of oil in exploration each year it is assumed that the end of this century will be the end of the oil in Iran.

The amount of energy in nuclear fuels, on the other hand, is many times greater than that of the estimated fossil fuels. Assuming that we learn to use nuclear fuels efficiently, they can supply Iran with energy for many centuries to come.

As an example of the increasing demand which will be placed on the fuel resources in Iran, let us look briefly at the projected electric power growth. According to the schedule of the Ministry of Water and Power the total capacity in 1978 is estimated to be 4100 megawatts, in 1980 it is expected to be about 5,000 megawatts and in 1988 8950 megawatts have been estimated (22). With these increasing demands it is obvious that care must be given to the use of fuel. And the "value" of the fossil hydrocarbon resources for such unique or special uses as raw materials for the chemical industry must be given full consideration.

In comparing the fuel, the cost of steam is influenced by two primary factors: the capital costs of the respective steam system, and the costs of the fuels themselves over the period of the life of the desalting plant (approximately a 30-year period). Nuclear plants require considerably more initial capital, but the fuel cost per million Btu's are considerably lower. Therefore, the trade-off between two plants is influenced by the scale of operation and the total amount of energy required. Generally, in large sizes, nuclear energy becomes increasingly

competitive because fuel cycle costs are lower for the nuclear power plant than for the fossil fueled plant. Thus the larger capital costs of nuclear plants, on a unit basis, become less important.

In Iran at the present time, gas, oil and mazut (a petroleum residue) are used for power production. The price of mazut is 1.71 mills per million calories (43 cents per million Btu) and that of gas oil is 3.52 mills per million calories (89 cents per million Btu), being very expensive when compared with the price of natural gas, which will be used after 1970 (22). The price of natural gas in Iran will be 0.84 mills per million calories (21.2 cents per million Btu) in 1970.

Fig. 3. 1. shows the yearly costs of 300 megawatts power plant (\$/kw-yr) using different fuels. This figure is prepared for Iran and assumed costs are tabulated on Table 3. I.

As Fig. 3. 1. shows for a plant larger than 300 mw the nuclear-fueled power plant is the only choice which is economically feasible and, therefore, will be used in this study.

#### B. Reactor Type Selection

It seems quite logical to assume that in general the reactors which are good for power only are also likely to be attractive for combined water and power production.

Nuclear reactors potential for providing low cost energy is the reason for their use for desalination. Several studies have been made on technical and economical feasibility of different types of reactors in conjunction with desalination plant. A study of single and dual-purpose plants using nuclear or fossil fuel has been made by the Catalytic

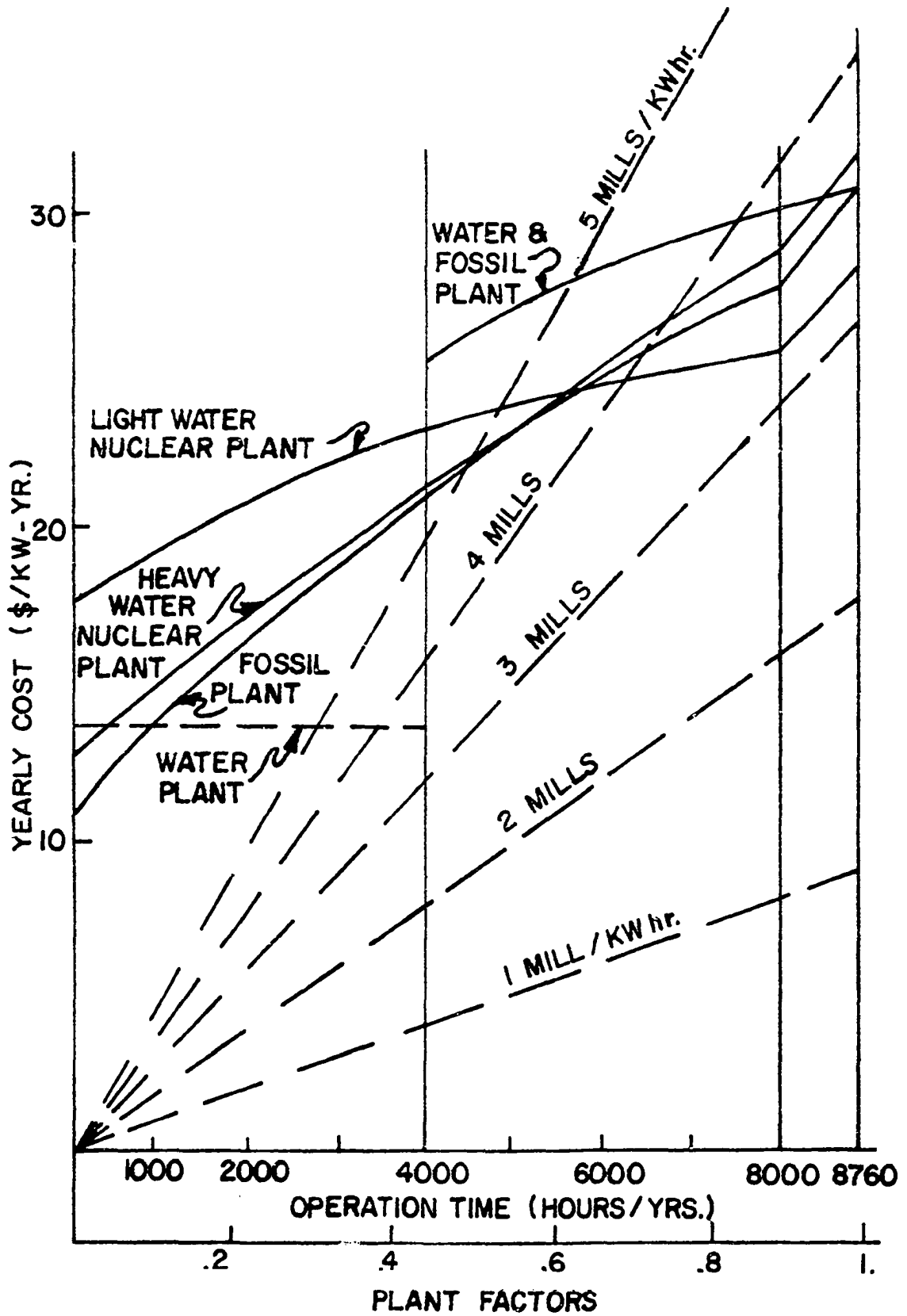


Fig. 3. 1. Yearly cost of 300 Mw power plant in Iran for different fuels

Table 3. I. Costs for 300 mw power plant considered in Fig. 3. 1.

	Fossil	Fossil & water <sup>a</sup> (180 mw fossil)	Nuclear	
			Heavy water	Light water
Capital cost (\$/kw-yr)	125	135	220	160
Life of the plant (yr.)	20	40 (for water only)	25	25
Fuel (mills/Mcal.)	0.84 (gas)	---	0.22	0.6
Operation and maintenance (\$)	3	2 (for water)	4	1.54

<sup>a</sup>The cost of power using dam water is based on the expenses of "Reza Shah the Great Dam" which is \$175/kw.

Company (8). Two categories of reactor plant have been considered. One is representative of low-temperature water reactors, namely the boiling water reactor and pressurized water reactor, and the other is representative of high-temperature reactors such as sodium-graphite reactor and the high-temperature gas cooled reactor. The results are in favor of low-temperature reactors.

The heavy water reactor has higher capital charge rate than the light water reactors. Moreover, in view of the present stage of development and commercialization of various reactor types, the confidence level for the estimating energy costs for present time and near future application for light water reactor was considered to be greater than for any other reactor type. Experience gained in various activities of the nuclear

industries, for example design, manufacturing, etc., has already led to cost reductions of light water reactors and will undoubtedly continue this trend in the future. Mass production and design repetition will also contribute to reduction of plant unit cost.

Unanticipated number of light water reactors have been purchased by the electric utility industries. These purchases have been made on the basis of warranties and economic extrapolation furnished by the light water reactor manufacturers.

In addition, availability to a reliable and cheap source of cooling water from the sea, in the case of this study, is another advantage of the light water reactor. So, light water reactor was selected for the production of energy in this complex.

The idea of boiling water reactor persisted, because the direct generation of steam within the reactor vessel itself is the most straightforward way of removing heat from the core of the reactor. By utilizing the latent heat of evaporation of water it is possible to extract heat at high rates. Also, if steam could be generated within a boiling water reactor and fed directly to the turbine, heat exchanger could be eliminated and large expensive pumps would be unnecessary.

The boiling water reactor's strongly negative local power coefficient from the boiling process exists throughout the core regardless of the magnitude of core dimensions (34). And this is another reason of selecting boiling water reactor for this complex.

#### IV. PRELIMINARY DESIGN OF NUCLEAR REACTOR

##### A. Design Criteria

The total thermal power requirement of the complex was calculated to be 5600 megawatts. Since there would be two reactors in the complex, each reactor should produce 2800 megawatts thermal energy.

The most advanced core design, the type used for Dresden 2 & 3 and that to be built for the BROWN's Ferry Station of the Tennessee Valley Authority, the U. S. A., will be used in this design. That is, a single cycle design, jet pumps, and steam separation within the reactor vessel would be used. A schematic diagram of the single cycle reactor system as employed in this complex is shown in Fig. 4. 1.

The nuclear fueled core, generating heat within the reactor vessel, boils water, producing saturated steam which then passes through internal steam separators and dryers and on directly to the turbine. The steam enters the high pressure turbine casing at about 965 psi and 545° F. Steam leaving the high-pressure turbine passes through moisture separator units prior to admission to the lower pressure turbine.

Operating temperatures in the reactor are governed by material considerations. The temperature selected is to avoid  $\text{UO}_2$  melting up to an overpower condition 10% above the rated power level. For the fuel rod size selected this results in a maximum core average specific power of 19.9 kw/kg uranium, which is the specific power for present commercial plants. The fraction of heat generated in the core assumed to be 0.96. All assumed data, as well as computed ones, are listed in Table 4. 1.

All aspects of the design are based on current technology and a



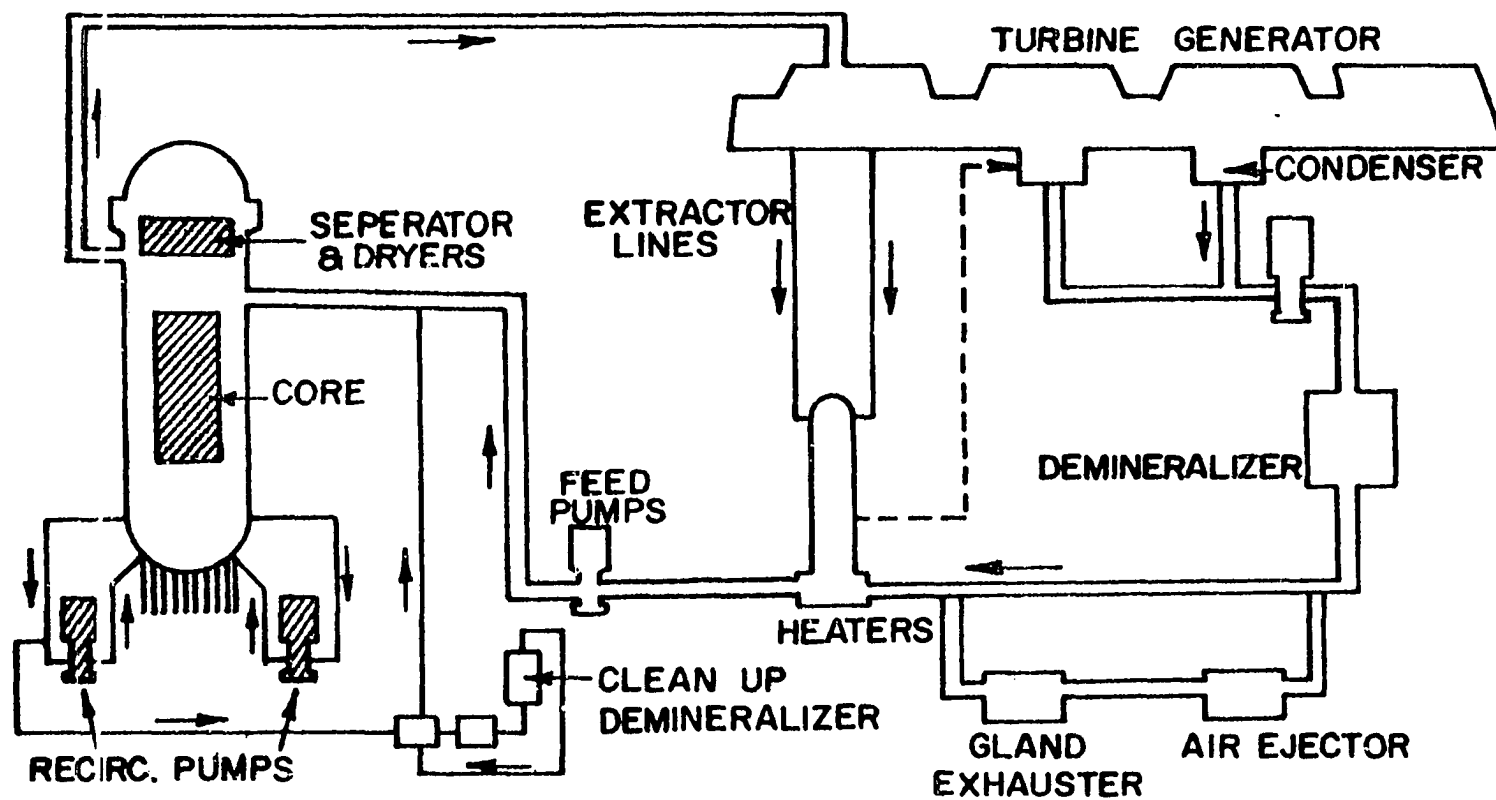


Fig. 4. 1. Single-cycle reactor system

realistic approach to design parameters and problems. A complete detail design could not of course be realized, thus this preliminary has dealt chiefly with the basic problems of reactor core, materials, heat transfer, and control and safety consideration.

## B. Materials

For the fuel  $\text{UO}_2$  was selected which is a ceramic. It has, like other ceramics, the advantage of high-temperature stability and general resistance to radiation. In addition uranium oxide is chemically inert to attack by hot water. This property of uranium oxide makes it attractive for use in water cooled reactor, where the consequences of a cladding failure could be catastrophic if the fuel material reacted readily with the water at the existing high temperature. Another beneficial property of the uranium oxide is its ability to retain a large proportion of the fission product gases even at the relatively high degrees of burnup. Its high melting point ( $\sim 5100^\circ \text{F}$ ) offsets its low thermal conductivity. Zircaloy-clad  $\text{UO}_2$  has been used in numerous reactors and it will continue to be the design approach into the foreseeable future. All experience to date gives reasonable confidence on its performance. Zircaloy was used, as clad, by virtue of its low neutron absorption cross-section.

Light water was selected for both coolant and moderator. Another attractive moderator, for light water reactor, is graphite which has been used for numerous designs. It, however, reacts with water vapor. Using graphite as moderator and water as coolant, the graphite should be clad. Another reason for using water for moderator is, water has

excellent slowing down power and small migration length for thermal neutron.

The water reactors have now reached the point where they are considered on an essentially equal footing with fossil-fueled units. The industry is benefitting from the substantial accumulation of experiences from many units now in operation or under construction.

### C. Preliminary Core Design

The components within the reactor vessel include the core, external components, control drive systems and jet pumps. The core consists of fuel assemblies, channel control rods, and sufficient instrumentation to monitor the status of the core at various stages of operation. Light water reactor cores are today a moderately well-developed state.

The geometrical configuration of the reactor was chosen to be cylindrical. An isometric cutaway of the reactor vessel showing the arrangement of typical components is given in Fig. 4. 2.

#### 1. Calculation of fuel load

In order to compute the amount of the fuel certain assumptions were made:

- a) Average burnup for fuel is 2.76%
- b) Fuel lifetime is 7900 hours
- c) 200 Mev energy released per fission
- d) One gram uranium-235 consumed is equivalent to 1 MWD
- e) 96% of the heat is generated in the core
- f) Plant factor is 95%, and
- g) Fuel enrichment is 2.5% uranium-235

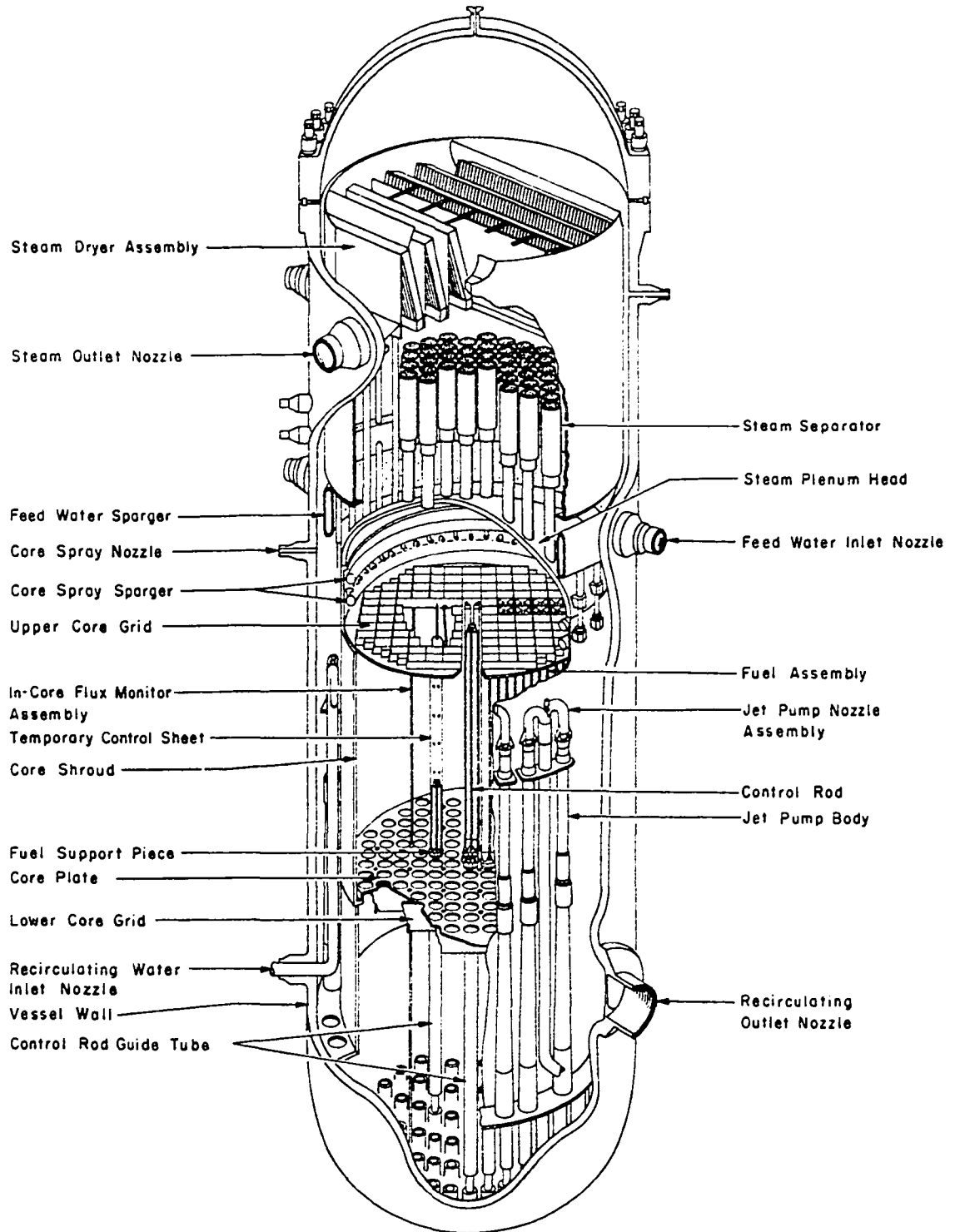


Fig. 4. 2. Reactor vessel and internals

The lifetime of any fuel element is limited by one of the several factors. These may be irradiation or fission product damage to the fuel; for solid fuel this will apparently be the limited factor. The fission products cause structural damage to the fuel and consequent fuel swelling.

Another factor which may limit fuel element useful lifetime is reactivity loss. This is the limit for thermal reactor.

In general the total fuel initially required is equal to the critical mass plus the amount of fuel consumed during fuel lifetime to maintain the required thermal power. Alternatively, the fuel load may be calculated on the basis of the maximum allowable burning. In this reactor like any other solid fuel reactor, because of a very low maximum burnup (less than 10%), this will be the determining factor.

For the calculation of the fuel load in this design the latter approach was used:

$$W_{U25} = N(\text{Atom U/cm}^3) V(\text{cm}^3) \frac{235 \text{ (g/g-at)}}{0.602 \times 10^{24} \text{ (at/g-at)}} =$$

$$NV \frac{235}{0.602 \times 10^{24}} \text{ g} \quad (4.1)$$

where  $W_{U25}$  is the weight of uranium-235 in gram,  $V$  is core volume in  $\text{cm}^3$ .

Using assumptions d, e, and f, one can write

$$0.96 \times 0.95 \times P \text{ (watts)} = \frac{N \text{ (at/cm}^3) \sigma_f \text{ (cm}^2) V \text{ (cm}^3) \Phi \text{ (n/cm}^2 \text{ - sec)}}{3.1 \times 10^{10} \text{ (fission/watt/sec)}}$$

then

$$NV = \frac{(3.1 \times 10^{10}) (0.96) (0.95) (2.8 \times 10^3)}{\sigma_f \Phi} \quad (4.2)$$

It is known that by using assumptions (a) and (b):

$$\text{Fission rate} = \frac{0.0276 \text{ N (at/cm}^3\text{)}}{7900 \text{ hr} \times 3600 \text{ sec/hr}} = N \sigma_f \Phi = 9.71 \times 10^{-10} \text{ N}$$

atom fission/cm<sup>3</sup>--sec.

Thus

$$\Phi \sigma_f = 9.71 \times 10^{-10} \text{ fission/cm}^3\text{-sec} \quad (4.3)$$

Substituting Eq. (4.3) in Eq. (4.2)

$$NV = \frac{(3.1 \times 10^{10}) (2.8 \times 10^9) (0.96) (0.95)}{9.71 \times 10^{-10}} \text{ atom U}^{235} \quad (4.4)$$

By substituting Eq. (4.4) in Eq. (4.1) one gets

$$W_{U^{235}} = 3185 \text{ kg U}^{235}$$

or

$$W_U = 127.3 \text{ Tonne uranium fuel}$$

$$\text{Specific power} = \frac{2800 \text{ Mw} \times 0.96 \times 0.95}{127.3 \times 10^3 \text{ kg U}} = 19.9 \text{ kw/kg U}$$

## 2. Core design

The standard General Electric boiling water reactor core lattice geometry for the core was chosen and it is shown in Fig. 4. 3. This basic core configuration is similar to that of most advanced reactor such

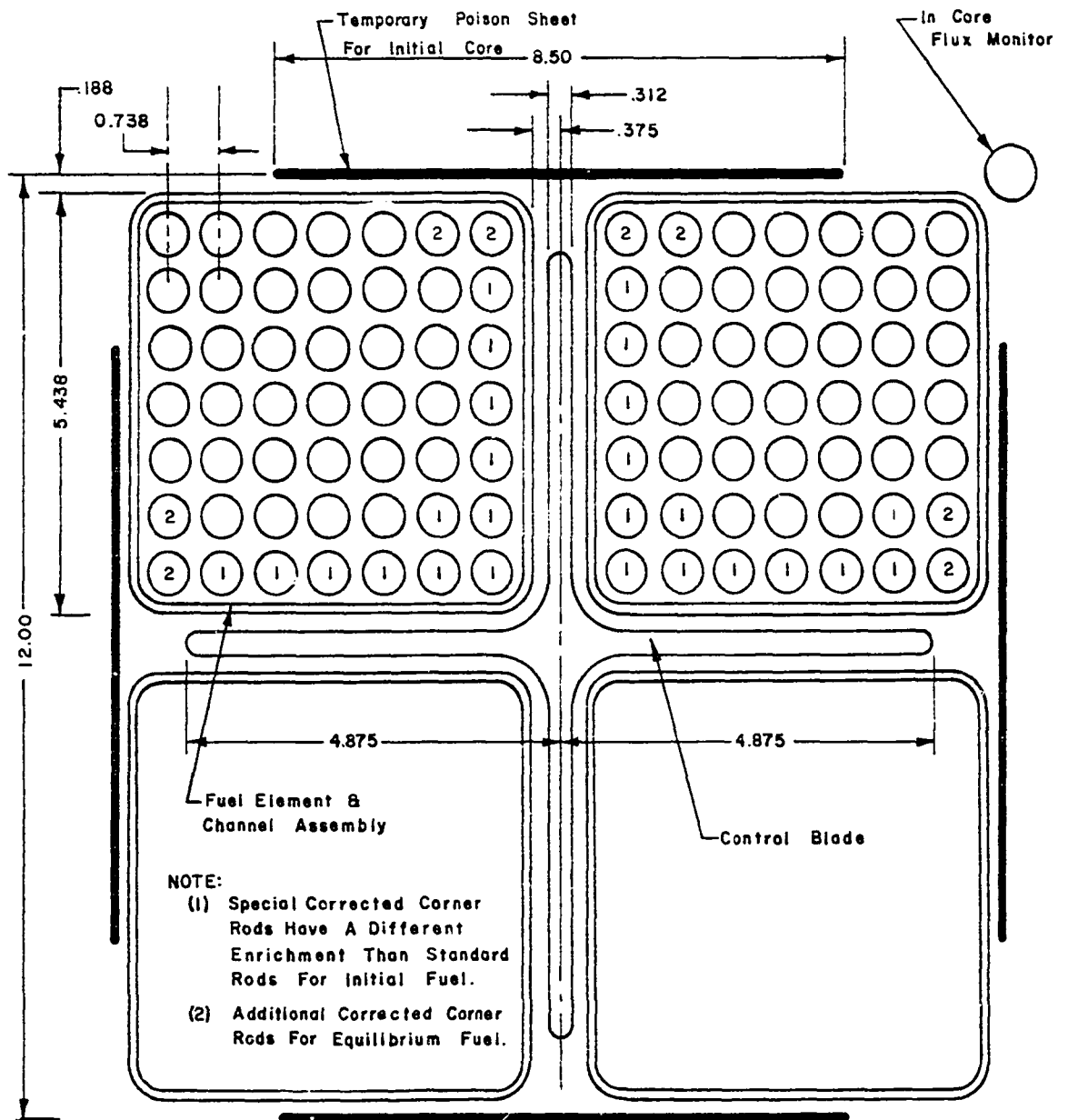


Fig. 4. 3. Core lattice

as Dresden 2.\* This core configuration was chosen because it has the characteristics of safety and flexibility.

Individual fuel assemblies in the core rest on fuel support pieces mounted on top of the control rod guide tube.

### 3. Fuel design

Each fuel assembly is made of a fuel bundle, consisting of a 7 by 7 array of fuel rods, enclosed in a Zircaloy-4 channel.

The fuel rod consists of 2.5% enriched  $\text{UO}_2$  pellets contained in Zircaloy-2 cladding. Fuel rod diameter was selected to be 0.562 inches. Construction detail of the fuel assembly is shown in Fig. 4. 4.

#### D. Heat Transfer Consideration

Heat transfer analysis provides information concerning heat removal and temperature in the reactor. From a technical standpoint of view, the power output from the core is limited by the "burnout". This is, for the planned operation conditions, the maximum heat flux is less than burnout value. In order to allow for local deviations from average behaviors the maximum flux is reduced by so-called "hot-channel" factor. For this design a "hot-channel factor" of 2.5 was used by referring to the related discussion and tables in reference 25.

General productions of critical heat transfer conditions for boiling in heated channel cannot be made with any reasonable certainty, hence, direct use of experimental data are preferred.

---

\*Dresden 2 & 3 will be an addition to Commonwealth Edison Company's Dresden Nuclear Power Station, located 50 miles southwest of Chicago Ill.



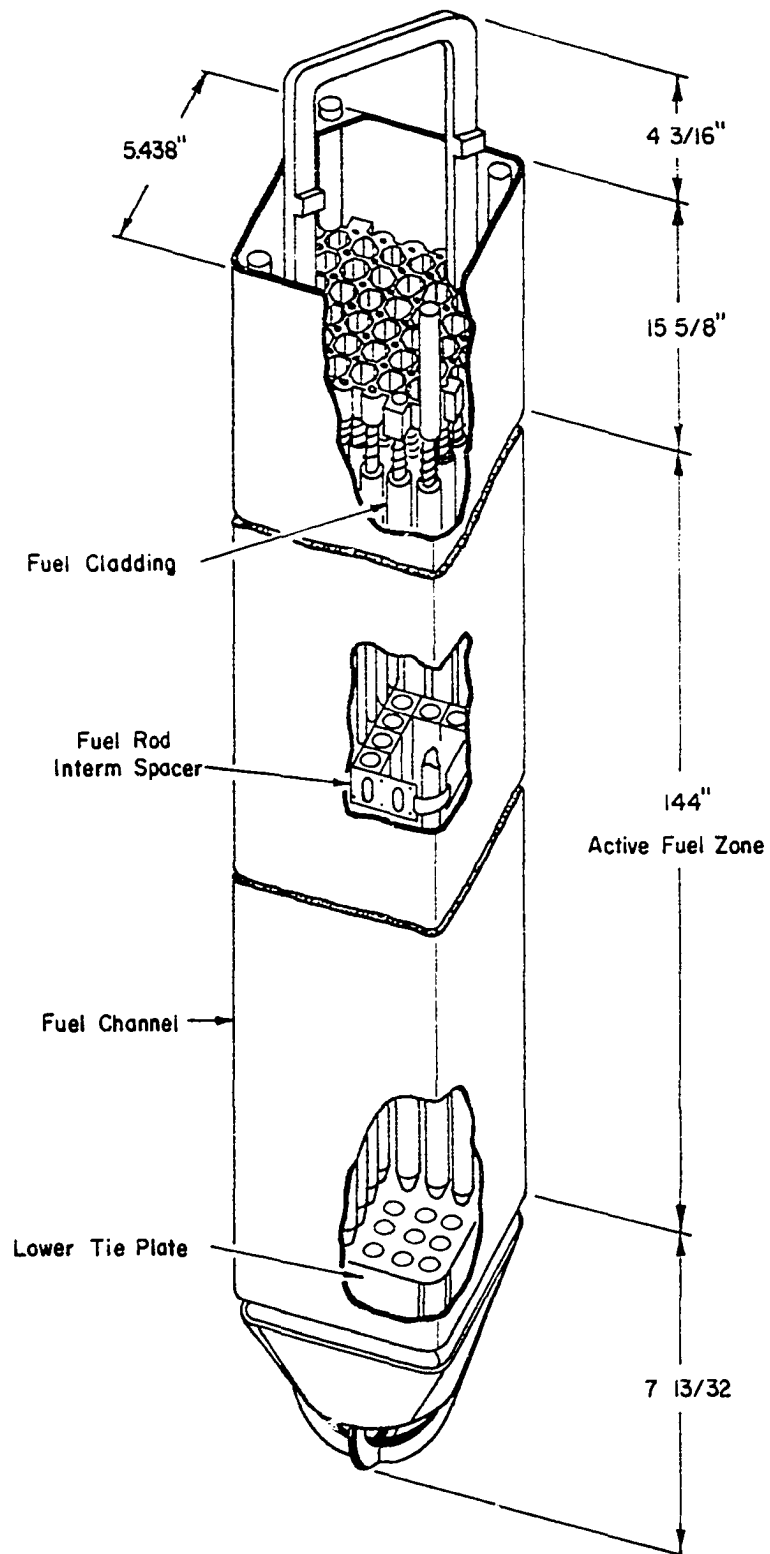


Fig. 4. 4. Fuel assembly

### 1. Determination of heat transfer area

For fuel rod of 0.562 inches the maximum heat flux is found to be 425,000 Btu/hr-ft<sup>2</sup>. Thus

$$\text{Average heat flux} = \frac{425,000}{2.5} = 1.7 \times 10^5 \text{ Btu/hr-ft}^2$$

The minimum heat transfer required is

$$A = \frac{\text{Thermal power}}{\text{Ave. heat flux}} = \frac{2800 \times 10^6 \text{ w} (3.4137 \text{ Btu/hr-w})}{1.7 \times 10^5 \text{ Btu/hr-ft}^2} = 56,200 \text{ ft}^2$$

### 2. Determination of number of fuel rods and assemblies

Using 0.562 inches outside diameter fuel rod 12 ft long, the surface area per rod is:

$$\text{Fuel rod surface area} = \pi dL = \pi \frac{0.562 \text{ in}}{12 \text{ in/ft}} 12 \text{ ft} = 1.765 \text{ ft}^2$$

The number of fuel rod required is:

$$\text{No of fuel rod} = \frac{56200 \text{ ft}^2}{1.765 \text{ ft}^2} = 31850$$

Since each fuel assembly consists of 49 fuel rods, thus

$$\text{No. of fuel assembly} = \frac{31850}{49} = 650$$

### 3. Determination of coolant mass flowrate

Since it was assumed that 96% of the total heat produced in the reactor was generated in the core

$$Q_{\text{Core}} = 0.96 (Q_{\text{total}}) = 0.96 \times 2800 \text{ Mw} = 2688 \text{ Mw}$$

The mixed mean core coolant outlet temperature was assumed to be 545<sup>o</sup> F and the inlet temperature was set at 375<sup>o</sup> F. These temperatures and  $T$  through the core are comparable to current boiling water reactor designs.

If one removes 2688 Mw thermal energy from the core,

$$Q_{\text{Core}} = m C_p \Delta T.$$

Where  $m$  is coolant mass flowrate through the reactor,  $C_p$  = coolant specific heat at average core temperature and pressure,  $\Delta T$  = average temperature rise of coolant through the core.

$$m = \frac{Q_{\text{Core}}}{C_p \Delta T} = \frac{(2688 \times 10^6 \text{ w}) (3.4137 \text{ Btu/w-hr})}{(0.638 \text{ Btu/lb} - ^\circ \text{F}) (170^\circ \text{F})} = 84.6 \times 10^6 \text{ lbs/hr.}$$

Assumed and calculated reactor design data used in this study are summarized in Table 4. I.

Table 4. I. Data for reactor core

---

Fuel material	UO <sub>2</sub>
Fuel pellet diameter, inches	0.488
Fuel pellet length, inches	0.700
Cladding material	Zircaloy-2
Cladding thickness, inches	0.032
Cladding outside diameter, inches	0.562
Active fuel length, feet	12
Number of fuel rods	31,850
Fuel rod array	7 x 7

Table 4. I. (Continued)

---

Rod per assembly	49
Number of fuel assemblies	650
Weight of $\text{UO}_2$ per fuel assembly, pounds	487.4
Total uranium loading, tonne	1273
Thermal output, Mw	2800
Fraction of heat generated in core	0.96
Reactor pressure, psi	1000
Total coolant flowrate, lbs/hr	$84.6 \times 10^6$
Core inlet temperature, $^{\circ}\text{F}$	375
Core outlet temperature, $^{\circ}\text{F}$	545
Brine temperature, $^{\circ}\text{F}$	260
Hot channel factor	2.5
Maximum heat flux, $\text{Btu/hr-ft}^2$	425,000
Average heat flux, $\text{Btu/hr-ft}^2$	170,000
Heat transfer surface area, $\text{ft}^2$	56,200
Specific power, $\text{kw/kg U}$	19.9

---

## E. Control and Safety Consideration

### 1. Introduction

Safety is a prime concern in any nuclear reactor. The higher performance requirement, increased capacity and/or complexity of this machine will require increased attentiveness to those features which could affect public safety.

The inherent mechanism which will limit the consequences of accidents in a reactor is a question of significant interest. Not only is it essential to guarantee that there is no danger to the public, but for a large power reactor, such as those used in this study, with an investment of more than \$50 million, it is also necessary to guarantee that there is no reasonable possibility of damage to the plant itself.

## 2. Reactivity parameters and their effects

a) Steam coefficient of reactivity      Steam coefficient of reactivity, which provides a quantitative measure of effect of steam on reactivity, is defined as the ratio of reactivity worth of steam and steam fraction.\* It could be either positive or negative in sign (23).

The first thing one must be certain of in designing a boiling water reactor is that at the design condition the steam coefficient of reactivity is negative. Having attained the negative steam coefficient, two desirable operating characteristics are obtained. The first is that the power is self-limiting. Thus, if by some unusual chance a large amount of excess reactivity were applied to the reactor, the power would increase moderately and then enough steam would be formed to remove this excess reactivity. The second desirable operating characteristic resulting from the negative steam coefficient is the self-regulation of the reactor power. The negative steam coefficient of reactivity implies a negative power coefficient of reactivity also. If the control rod of the

---

\*Steam fraction is the fraction of the coolant channel volume occupied by steam.

reactor is kept in a fixed position the reactor will try to maintain a constant amount of steam in the core. This means that the power of the core will have to stay constant.

Negative coefficient of reactivity will increase with increasing temperature and increasing steam content for enriched reactor (23).

b) Doppler coefficient      The Doppler effect is due mainly to neutrons with energy less than 10 kev. The broadening of resonances leads to a lessening of the flux depletion at these resonances, with a resulting increase in interactions taking place at these energies.

The Doppler effect is made up of a positive and a negative component. The positive component is due to fission rate increase and negative one is due to increase in neutron capture. The sign of the overall effect depends on the relative densities of core materials, the spectrum, and the temperature of the reactor. Generally, the Doppler coefficient is positive for systems highly enriched in fissile materials, and it is negative for low enriched systems, such as that designed in this study.

c) Temperature coefficient      Temperature coefficient of reactivity consists of a) coolant and moderator temperature component, which is due to density decrease of water with temperature increase. This effect is usually small but negative, because of larger contribution of the resonance escape probability which is negative, b) fuel temperature coefficient, which is generally negative (15) for natural or moderately enriched uranium fuel.

A negative temperature coefficient of reactivity is desirable since it tends to counteract the effect of transient temperature changes during

reactor operation.

d) Delayed neutron coefficient      Since the fraction of delayed neutron for uranium-235 is 0.0065 which is very large compared to Pu<sup>239</sup> (for Pu<sup>239</sup>,  $\beta = 0.0021$ ), the amount of reactivity needed to go prompt critical is proportionally more. This coupled with the fact that the neutron lifetime of prompt critical is  $10^{-7}$  second, means that generally thermal reactor has less of a chance to go prompt critical and then have a much less severe transient which leads to meltdown or disassembly of the fuel.

### 3. Safety analysis

Future generations of the boiling water reactor will benefit from the experience of several years of operation of many boiling water reactors under operation in the United States, Italy, Japan, and Germany, as well as experience from reactors under construction.

From this experience boiling water reactor will incorporate many inherent and engineered safeguards:

a) The boiling water reactor has the inherent feature of regulating itself. If the reactor's normal power tends to go up, the increased formation of steam bubbles decreases the volume of water, causing a reduction in thermal power.

b) The plant will remain safe even if power supply to the reactor recirculating pumps is interrupted. In the event of an interruption, natural circulation of water within the reactor vessel will sustain a rate of water flow sufficient to remove heat from the reactor core until control of the fissioning process is taken over by insertion of control rods.

c) Small instruments, called "in-core monitors", will be located throughout the reactor core to measure thermal power and to guide personnel in controlling its distribution.

d) Positive, prompt closures will be capable of isolating the reactor system.

e) The overall containment system will include multiple safety barriers: The Zircaloy fuel cladding, the reactor vessel, the drywell, the water-filled suppression vessel, and, finally, the reactor building.

f) Control rods will be actuated for rapid insertion by hydraulic energy.



## V. THE PRODUCTS OF THE COMPLEX

### A. Introduction and Criteria

As shown in Fig. 1. 1. an agro-industrial complex consists of a large nuclear reactor station producing both electricity and water. The electricity would be consumed in adjacent industrial processes and for pumping water. The desalted water could be used for municipal and industrial processes, and the irrigation of the agricultural fields of the complex.

In this chapter, first the costs of water and power will be estimated and then the industrial and agricultural products of the complex will be discussed.

The estimation of the costs of water and power is dependent on the ground rule used in the evaluations. Since the water and electrical power required for industrial and agricultural products would be produced within the complex, the cost of these items will not be estimated directly, but rather all the capital and operating costs for producing these inputs will be included in arriving at the total costs of overall complex. In other words, the total investment, operating costs, income, and the rate of return for integrated nuclear-powered agro-industrial complex will be estimated.

In order to evaluate the economy of industrial and agricultural products, the cost of water and power were estimated.

In selecting the industrial products, the break-even power cost comparisons are performed by increasing the price of electricity until the manufacturing cost for electric-intensive process equals the

manufacturing cost for the competing process. To evaluate the relative merit of the complex the internal rate of return (36) method is used. The internal rate of return is the interest rate at which a particular project will just break even; that is, the present value of expenses, including all capital charges, will just equal the present value of income from sale of products.

The annual fixed charge rate usually includes interest on borrowed money, return on equity, depreciation, federal, state and local taxes and insurance. In Iran the annual fixed charge is assumed to be 8% because of favorable interest rate (about 6%) and lack of taxes.

The service lives for all industrial units and the reactor were assumed to be 15 and 30 years respectively. There is no information on nuclear power station costs for Iran. Consequently, estimation has to be made on United States estimates. It should be based on non-indigenous design and fabrication of the principal reactor and turbogenerator components, although much of the erection and installation as well as small components may be provided in Iran.

The United States Oak Ridge National Laboratory estimated that the capital costs for nuclear power stations to be built outside the United States would be 12% greater than total costs in the U. S. The estimations are based on experiences in the Philippines, India, and Israel. The same assumption will be used in this study.

As a result of correspondence with the Iranian Ministry of Water and Power, Plan Organization, and some friends in the Ministry of Economy valuable information, for example, the prices of raw materials and products of the complex, has been gained. The cost and price data are

based on 1967 levels.

The nuclear-powered agro-industrial complex considered in this study consists of a power plant (nuclear fueled), the industries which utilize the power produced, a seawater desalination plant and an irrigated farm. In order to avoid the internal transactions such as the sale and purchase within the complex of electric power, steam, and desalted water or other by-products, evaluation has been made by the tabulation of capital investments, annual operating costs, and annual income from the sale of the products. This solves the problem of how to allocate to electric power and to water the cost of a dual-purpose reactor producing both products. The costs of facilities such as a harbor, public utilities, and housing for workers and their families and for service personnel. Income was calculated from the sale of products at Iranian market price.

Electric power capacity was included not only for the need of complex but also for transmission and sale to the other communities.

#### B. Estimation of Power and Steam Costs

The principal motivating factor leading to this study is the low costs that have recently been estimated for electricity produced using nuclear reactors now under construction or development.\* Depending on plant size, electricity production costs for nuclear stations in the range of 2.4 to 4 mills/kwhr have been announced for plants under construction in 1967 (46).

---

\*As a result of this low cost energy and development of desalting technology the cost of the desalted water is estimated to be relatively low.

The cost of light water reactor, used in this study, is based on a survey of information available on mid-1967 (13, 25, 39, 46).

In addition to producing power the reactor in the complex can supply steam for desalting the seawater. Therefore, to facilitate the estimation of capital and operating costs of the station the power plant was considered to consist of two islands namely nuclear island and the turbo-generator island.

The costs for a number of stations of about 1000 Mw capacity in 1966 and 1967 fall in the range \$115 to \$155/kw, including charge for interest during construction but not including the cost of land (25). In this study the cost of \$135/Kw  $\pm$  15% for capital cost, excluding land, fuel, and transmission facility, was considered. This is a conservative cost since the effect of increasing construction experience, technology improvements, and number of reactors were not considered.

The operating costs for nuclear power station are fuel cycle cost, operating and maintenance costs, and insurance costs.

The annual costs for operating and maintenance, as well as nuclear liability and property damage insurance, were estimated using references 25, 39 and 50.

The total cost estimation is based on following factors:

Plant load factor	0.9 (7900 hr/year)
Thermal efficiency	32.6% (net)
Number of reactor per station	2
Size of single reactor	600 Mwe
Fixed charge	8%/year

Assumed plant life	30 years
Time of construction	5 years

The concept of agro-industrial complex evaluated in this study impose large, steady energy loads on the generation station. Consequently, the load factor was considered to be greater than is normally the case for the ordinary nuclear power station.

Total costs for producing steam and power are a function of station generating capacity and the fixed charge. Fig. 5.1 shows the cost of electrical power and steam as a function of size for 8% fixed charge under United States conditions.

Reliability considerations will dictate the use of two or more reactors per station for large nuclear power stations, because it is not possible to tie in with an electrical grid of substantial capacity in South coast of Iran.

#### C. Estimation of Water Cost

For the case of agro-industrial complex, it is necessary to determine the actual unit costs for producing each of the two products, water and power. To do that, one has to allocate arbitrarily a fraction of, for example, the nuclear capital and operating costs to the water produced. Although this should be done for the plants which sell these products, it is required in this study where the water and power are consumed within the complex.

U. S. Oak Ridge National Laboratory (50) used an approximate method for illustrating the range for the absolute cost of water as a function of fixed charge for different plant capacities. Fig. 5.2. shows the cost

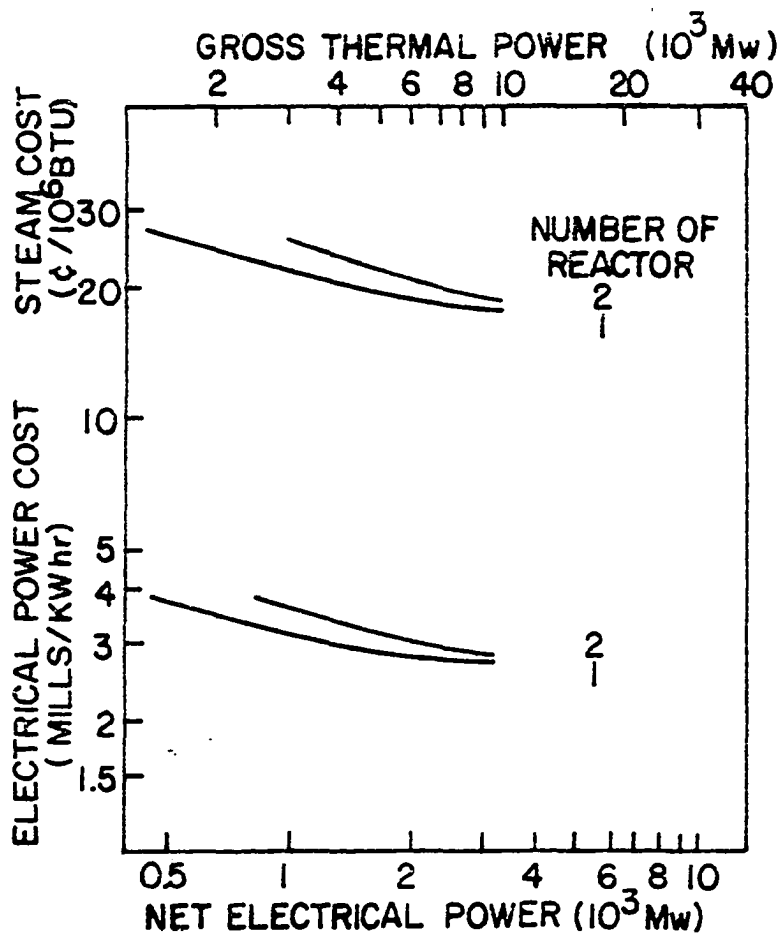


Fig. 5. 1. Prime steam and power costs for the LWR

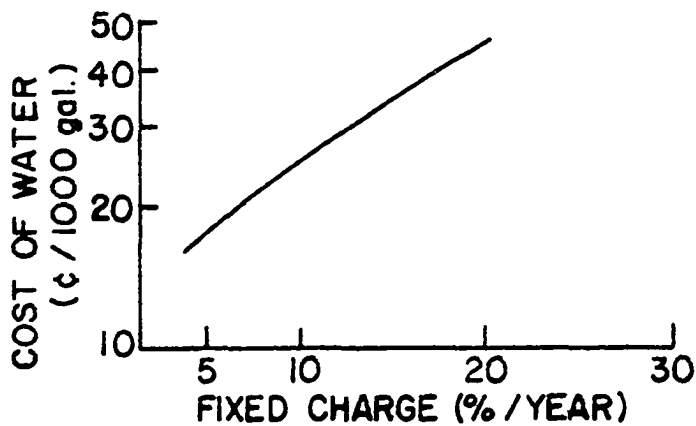


Fig. 5. 2. Cost of water from 500 Mw dual-purpose nuclear desalting plants

of water from a dual-purpose nuclear plants using light water reactor. Performance ratio of 12 was used in determining the cost of evaporator and relative amounts of water and power produced.

The optimumization of water-to-power production ratio involves a balance between incremental costs and incremental returns which is not possible in this study. Water and power are intermediate products in an agro-industrial complex. Therefore, their value depends on the value of the final agricultural and industrial products.

#### D. Industrial Products

Electricity, steam, and water are basic to nearly all chemical manufacturing processes. All of these materials are produced in the complex. The advantages of several different chemical and manufacturing plants in a complex, which could be located in a single site or separated by a distance up to 30 miles apart, is that the common-use facilities can be shared and also intermediate or waste products from one process can be used by another process.

In selection of industrial processes first consideration should be given to the product needs and export potentials of the country.

Production of nitrogen and phosphorus fertilizers is given high priority because of present and growing food needs. The need for building materials such as iron, steel, aluminum, portland cement and need for basic chemicals, such as caustic-chlorine and acetylene, which would be used by secondary industries throughout the country, is also considered.

Attention is given to the products which can be produced from seawater. In warm South coast region of Iran, solar evaporation would

probably be the main method used to further concentrate the brine of the desalination plant, which, in this case for vertical tube evaporator, is 2.5 times as concentrated as seawater.

The production costs for 17 chemical products were studied intensively at the U. S. Oak Ridge National Laboratory (50). In order to make as complete an evaluation as possible, computer codes were developed and used. The detailed computational methods used and a full review of the procedures, including a brief description of the computer codes, is presented in reference 14.

Because of lack of information concerning to the prices of the raw materials and the products in present and future market in Iran, the author did not repeat the above mentioned evaluation studies under Iran conditions. The manufacturing costs and the values of parameters (plant capacity, utility cost, interest rate), considered in this study, were obtained from the tables prepared by H. E. Geoller (14).

In order to obtain a measure of economic attractiveness (feasibility) of the processes being used in this complex for the different products, costs for the high energy-intensive processes (used in complex) were compared with the costs for conventional non-electrolytic method, if available, of producing each product.

Fig. 5. 3. shows the comparison of steam-methane in Iran (price of natural gas is 21.2¢/million Btu) the price of power must be less than 1 mill/kwhr. The possibility of attaining this power cost is remote. The manufacturing cost of ammonia by steam-naphtha reforming is somewhat higher than by steam-methane reforming because of a more expensive raw



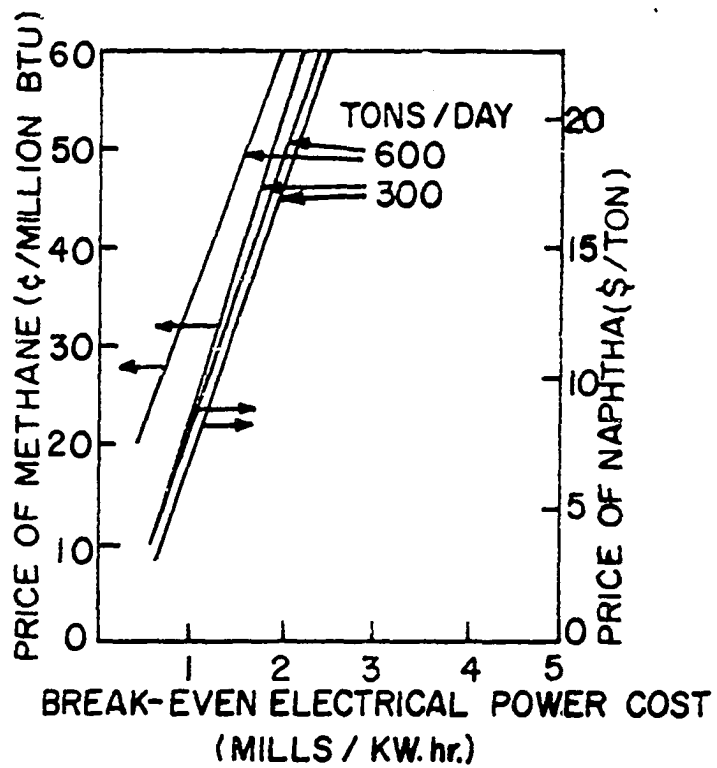


Fig. 5. 3. Comparison of steam-methane and steam-naphtha reforming with electrolytic hydrogen for ammonia production

material. Fig. 5. 3. shows that naphtha at \$20/ton (price at refinery) is equivalent to natural gas at 53¢/million Btu.

The break-even power cost for the production of ammonia-derived fertilizer would be about the same as for ammonia itself. This results from the fact that the secondary products use very little electricity compared with that needed for water electrolysis (to produce hydrogen) and ammonia synthesis.

Computed gross manufacturing cost of phosphoric acid versus power cost for two alternative processes, the electric furnace and wet acid methods, indicates that the power cost at which the furnace process (to be used in the complex) can compete is about 5.5 mills/kwhr. This value was computed for plant capacity of 600 tons/day  $P_2O_5$  and 8% fixed charge.

The production cost of aluminum was also reviewed. Since the Bayer and Hall processes for the production of alumina ( $Al_2O_3$ ) and aluminum, respectively have no competing processes in industrial use today (50), manufacturing costs were computed directly. For the plant capacity of 275 tons of aluminum, with the cost of bauxite \$8 per ton, the gross manufacturing cost of aluminum would be \$570/ton for 3.4 mills/kwhr electricity produced in the complex.\*

The manufacturing of chlorine was also considered. Since electrolysis of the brine is the only significant source of chlorine throughout the world, no other production could be considered. For plant capacity of 600 tons/day of chlorine and power 3.4 mills/kwhr the manufacturing

---

\*Gross manufacturing cost of aluminum produced in the northwestern United States is \$650/ton.

cost of chlorine is computed to be about \$34/ton. No break-even power costs are provided since no comparison with a competing process could be used.

A comparison was made of the production of acetylene from naphtha by the electric arc and "partial oxidation" processes. This study was made by W. E. Lobo, consulting chemical engineer of the U. S. Oak Ridge National Laboratory for India and the U. S. (50). With a fuel value assumed of \$0.40/million Btu, the cost of acetylene comes out nearly 50% higher than calculated for the arc process with power value of 4 mills/kwhr. It is logical to believe that, the production of acetylene by the electric arc, in this complex where cheaper power is available, is in a more favorable position.

As mentioned before an agro-industrial complex located on an arid coast has the advantage of being able to build a solar salt works to utilize at least part of the concentrated brine effluent from the seawater evaporator. In addition to producing salt, the salt and its biterns by-products are the source of several other products. The salt itself can be used for production of chlorine, caustic hydrogen, hydrochloric acid and sodium carbonate, and the biterns are the raw materials for the recovery of potassium fertilizers, anhydrous magnesium chlorine, magnesium metal, and gypsum for sulfuric acid, and cement manufactures.

If about 2% of brine effluent from a 500 Mgd seawater evaporator, operating ratio at 2.5, be utilized by solar salt works, about 500,000 tons/year of salt would be produced. At above-mentioned concentration ratio the saving in land required over the use of raw seawater for solar salt production is about 40%.

Manufacturing costs for recovery of potassium sulfate and potassium chloride were found to be \$15 and \$10 per ton respectively at a fixed charge of 8% and electricity cost of 3.4 mills/kwhr. The market price of potassium chloride in Iran is \$22/ton.\* Therefore, the production of potassium fertilizer in complex is favorable. In addition, salt and other chemical yields from a solar works will increase with time because of an increase in imperviousness of salt works and bitterns pond bottoms, thereby reducing leakage.

Cement and sulfuric acid are commodities which are basic, especially in Iran as well as other developing countries. Gypsum recovery from seawater concentrates by solar evaporation provides a source of sulfuric acid, especially when the cement is co-produced. A comparison has been made between the plant that uses fossil fuel as a heat source and that uses electric heating. At a fixed charge of 8% the break-even cost of power-intensive process is less than 2 mills/kwhr. The break-even power cost for gypsum is 8 mills/kwhr. Thus the process is worth considering.

The recovery of  $\text{MgCl}_2$  from solar salt bitterns using fossil fuel is much less expensive than power intensive process. Therefore, fossil-fueled plant should be considered for recovery of  $\text{MgCl}_2$ .

Magnesium is another by-product of brine. Traditionally, magnesium metal is produced from  $\text{Mg}(\text{OH})_2$  obtained from seawater. However, magnesium can be produced from  $\text{MgCl}_2$  obtained from brine effluent at lower manufacturing cost because chlorine is produced instead of being consumed.

---

\*The U. S. f.o.b. price of  $\text{K}_2\text{SO}_4$  and  $\text{KCl}$  are \$25 and \$16 per ton. The price of  $\text{K}_2\text{SO}_4$  in Iran is unknown.

### E. Agricultural Products

This section is based on the following general assumptions, or ground rules:

1. Emphasis would be primarily on production of food products such as grain, fruit crops, oil crops, legumes, and vegetables.
2. The most efficient farm system and modern technology would be used.
3. Systems of production and marketing would be highly efficient.
4. The technical and economical feasibility is studied. Other factors such as political and social factors, which are not possible to consider in this study, is left for further investigation.

The cotton is added to the crops because its fiber is a valuable raw material and oil from the cotton-seed is also a useful food product.

The large amount of agricultural by-products unsuitable for human consumption could be used to develop the animal production. Livestock agriculture should be studied in detail, since Iran imports meat. Because of lack of pertinent information it was not included in this study.

Data required on the total annual water requirement of various crops considered are furnished by the Water Resource Planer Group, Plan Organization of Iran. In agro-industrial complex, however, less water will be used since the optimum economic irrigation treatment\* would be applied.

Crop yield data were required for the economic evaluation of the various crops. Since there is no such data available, the judgment of crop specialists engaged in research and development has been used (50).

---

\*The amount of irrigation water which yields the maximum return.

The crops, their water requirements, and their yield are listed in Table 5. I.

The amount of fertilizers required for each crop should be determined by soil, previous crop, and other factors. For the cost estimates, the amounts used in the irrigated desert valley of the southwestern U. S. were adopted. The assumed fertilizer rates are listed in Table 5. I.

In order to select the crops, costs and return was evaluated. In this evaluation labor was charged at 25¢/hr. Fertilizer costs used are N, 4¢/lb;  $P_2O_5$ , 6¢/lb and  $K_2O$ , 7¢/lb. Water was charged at 20¢/1000gal taken from Fig. 5. 2. The calculated costs are based on a number of costs studied in the United States (16b, 32, 53).

For calculation of gross sales as a comparison, the world market prices were used (to be conservative). Though only cotton lint is exported from Iran and should be considered at world market price, and for the other crops 30% above world market price is appropriate, as they are imported or are not enough to be exported.

Price assumptions, calculated gross sales, and calculated return above direct crop costs\* are shown in Table 5. I. The return shows the income available to pay capital charges and their indirect costs.

The relationship of cost to price levels for wheat is shown in Fig. 5. 4. In this figure indirect cost assumed to be \$150/acre-yr.

---

\*Direct costs include the cost of seed, labor, machine operation, fertilizer, water, power, and storage and marketing.

Table 5. I. The crop, the water required, yield, fertilizer applied, and return

Crop	Water required (inches)	Crop yield (lb/acre)	Fertilizer applied (lb/acre)		Crop unit price (\$/cwt)	Return above direct cost (\$/acre)
			N	P <sub>2</sub> O <sub>5</sub>		
Citrus	51.2	44,000	130	30	3.00	199
Cotton (lint seed)	33.3	1,750	300	100	22.00	100
		2,800			2.40	
Drybeans	20.6 <sup>a</sup>	3,000	70	70	6.00	30
Peanuts	34.5 <sup>a</sup>	4,000	120	80	7.00	- 13
Potatoes <sup>b</sup>	15.6	48,000	200	120	1.40	128
Safflower	33.6 <sup>a</sup>	4,000	200	50	4.00	- 69
Sorghum	27.6 <sup>a</sup>	8,000	150	80	2.11	- 28

<sup>a</sup>Water required for this crop was not available for Iran. Data from Reference 55 was adopted.

<sup>b</sup>Potatoes also requires 45 lb of K<sub>2</sub>O fertilizer per acre.

Table 5. I. (Continued)

Crop	required (inches)	Crop yield (lb/acre)	Fertilizer applied (lb/acre)		Crop unit price (\$/cwt)	Return above direct cost (\$/acre)
			N	P <sub>2</sub> O <sub>5</sub>		
Soybeans	33.4*	3,600	100	50	4.84	- 50
Tomatoes	20.8	60,000	200	150	1.20	313
Wheat	21.4	6,000	200	50	2.66	15



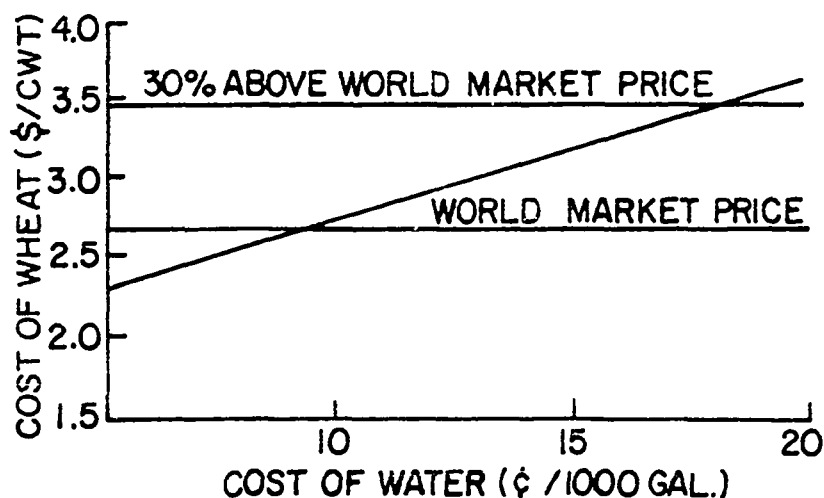


Fig. 5. 4. Effect of water cost on total cost of wheat

It is interesting to note that the break-even water price for wheat at 30% above world market price is 17.5¢/1000 gal. And for water price at 20¢/1000 gal., estimated for this complex, the wheat price is only 20¢/cwt above the price occurring in Iran.

The most profitable crop combination involves selection to maximize return above direct cost for the system as a whole. The crop combination for the farming system was hand calculated to provide a wide range of crops, minimum storage requirements, and high quality food. In selection the crops, consideration was given to economic returns. That is, the crops were chosen so that to maximize the profit. The high value crops and their acreages are listed in Table 5. II. The base acreage can produce two crops per year. Additional winter acreage may be added, since water requirement is higher in hot summer months than in the winter. A total of 120,000 acres is used with two crops produced per year and an additional 40,000

acres is used in winter.

Table 5. II. Crop selected and land used

Crop	Land use (acre)	
	Summer	Winter
Citrus	5,000	5,000
Cotton	20,000	
Drybeans	95,000	
Potatoes		30,000
Tomatoes		5,000
Wheat		120,000

## VI. ECONOMIC ANALYSIS OF THE COMPLEX

To avoid the problem of cost income allocation within the multipurpose plants, for example, dual-purpose nuclear power plant or fertilizer plant, in the economic analysis, the entire nuclear-powered agro-industrial complex is considered as a single economic unit. That is all investments, costs and all <sup>revenues</sup> were aggregated without any allocation of cost or income to the various products or subproducts. The value of the products is computed as the summation of the annual production of the products times the sale price.

The capacities of the industrial products were assumed to be 1280, 342, 1130 tons per day for  $P_4$ , Al, and caustic respectively. These capacities were selected considering the need of the country in late 1970's and because the computer programming for 12 three-product runs of different capacities, under non-United States conditions, shows that this capacity combination, has one of the highest return on investment. The total electrical power required for selected industrial products is 1021 Mw (14).

Using data from Table 5. I and 5. II, water required is computed to be 500 million gallons per day. In the calculation of water capacity of the complex the water required for domestic uses was also considered.

Electric power required for evaporator is 0.142 Mw/Mgd (page 26) or 72 Mw total. Irrigation pumping power at the rate of 207 hp/Mgd for 500 Mgd capacity would be 76 Mw. Considering 31 Mw for grid power the total electrical load on the reactor would be 1200 Mw.

Since the product of the reactor is not only electricity and an

evaporator is included to produce fresh water, the use of back pressure turbines is desired. The thermal efficiency of back pressure turbines is 0.2137 Mw (electrical)/Mw (thermal).

#### A. Capital Costs

Capital costs for fully constructed nuclear reactor and turbogenerator islands are computed using parameters given in Table 4A.1 of Ref. 50 for "two-unit system" and using equations:

$$C_N = C_{NR} \left( \frac{P_t}{PR_t} \right)^{-n}$$

$$C_{TC} = C_{TCR} \left( \frac{P_e}{PR_e} \right)^{-m}$$

where  $C_N$  = dollars/Kw (thermal) for nuclear island at desired thermal power level  $P_t$ , in megawatts.

$C_{TC}$  = dollars/Kw (electrical) for complete turbogenerator-condenser island for a condensing turbine system of electrical power level  $P_e$  in megawatts.

$P$  = Desired power level, Mw

$R$  = Reference (base or power level)

$n$  = Scaling factor for nuclear island

$m$  = Scaling factor for turbogenerator-condenser island

$t$  = thermal

$e$  = electrical

The computed capital cost for nuclear power station is increased 12% for Iran, because the available parameters are for the U. S. conditions.

Capital investment for vertical tube evaporator including indirect charge is computed by referring to Ref. 50 and 47. The performance ratio assumed to be 12 lb of water per 1000 Btu. Different methods could be used to prevent the scale on the heat transfer surfaces in the evaporator. This study assumed the use of the hydrochlorine acid, since chlorine does not have any value in Iran, and it is a subproduct of the complex. The capital investment of a recombiner (for hydrochlorine acid treatment of seawater) equipment is:

$$C_A = 0.096 [0.00332 (W_B + W_P)]^{0.6}$$

where  $C_{EM}$  capital investment of recombiner, millions of dollars,

$W_P$  = fresh water output, Mgd

$W_B$  = brine blowdown, Mgd

For vertical tube evaporator  $W_B = 1/2 W_P$

Capital investment for the United States industrial complex was first computed by reference to data available in the literature (14, 50). Then, the indirect costs (recovery of and return on investment, interest on working capital) for industrial processes were increased in proportion to the increase in capital costs for the construction in Iran, while the labor costs considered to be halved in calculating the direct costs (raw material, labor, overhead, etc.).

To compute the capital investment costs for the farm, the initial cost of obtaining ownership or use of land is assumed to be zero, since the area is unpopulated and there is no sale price. The land, however,

must be prepared for irrigation and agricultural use.

Since there is no information about the physical-chemical status of the soil at the site, it is impossible to determine the cost for reclamation. The cost of reclamation has been estimated to be from zero to \$150 per acre (50). A cost of \$65 per acre was allowed for in this study. The cost of cleaning, leveling and smoothing of the land is estimated to be \$30 per acre. This estimation is based on the experimental data from Hawaii, California, Colorado (U.S.A.) and Australia (37).

Other costs of the agricultural complex are the cost of irrigation system, farm machinery, storage and building, and research station. The total cost is estimated to be \$950 per acre for this study. The break-even in per acre investment costs in the agricultural complex are listed in Table 6. I.

The costs of harbor facilities includes building the harbor\* and administration facilities. For agro-industrial complex, the capital investment for a harbor may be approximated using the equation:

$$C_H = 18 \left( \frac{Mwe}{700} \right)^{0.6}$$

Where  $C_H$  is capital cost, millions of dollars, and Mwe = power plant net electrical output in magawatts after deduction of grid power.

---

\*Since there is harbor facilities in Bandar Abbas, it needs only to be enlarged to meet the requirement. In this study, however, somewhere near the border of Iran and Pakistan is considered.

Table 6. I. Total investment (dollars) per acre of land

Item	Cost (\$/acre)
Land and land improvement	200
Irrigation system	222
Farm machinery	100
Storage and building	225
Research station	3
Total cost	950

A housing must be provided for the workers of the agro-industrial complex and their service workers including their families. Adding to the housing the sanitary, water facilities, and streets, computation should be made for provision of a town. Thus assuming 15,000 workers for the complex and assuming two non-workers for each worker, the population of the town would be 45,000. The capital investment needed to provide houses and

facilities for the workers and their families was calculated based on allowance of \$500 per person.\*

For the sale of power to a grid which can be used as a grid-tie interconnection to provide reliability when only one reactor is constructed and working, it is necessary to have the facility. The capital investment, in millions of dollars, is given by

$$C_G = 7.3 \left( \frac{L_G}{250} \right)^{0.43}$$

$L_G$  is the grid power, Mw. This investment is based on power transmission over a 100-mile distance.

Fuel inventory capital, a non-depreciating item, is computed according to \$6333/Mw (thermal) (13, 50).

Working capital for complex is assumed to be one-third of the annual operating costs of the complex (four months operating costs).

#### B. Annual Operating Costs

Several estimations of operation and maintenance of the light water reactor power station were reviewed (24, 25). The results were in good agreement and the average value for nuclear reactor island (two units) used in this study was determined. Similar estimation was made for the turbine generator island. To compute the insurance, the following relationship was used:

$$\text{Insurance (dollars/year)} = 30 P_t + 260,000 U$$

---

\*U. S. ORNL assumed \$300 per person, which the author believes is too low.



where  $P_t$  is thermal power of the nuclear station, Mw, and U is number of units (reactors) in the station. This was included in nuclear island annual operation costs.

For calculation of fuel cycle cost several literatures (25, 39, 50) were reviewed and fuel cycle cost assumed to be 0.435 mills/kwhr (thermal).\*

Operation and maintenance costs for an evaporator are calculated using the equation

$$C_{EOM} (\$/\text{yr}) = 4350 \left( \frac{C_E}{101} \right)^{0.7} 365 \times LF_e$$

where  $C_E$  is capital cost of evaporator (millions of dollars) and  $LF_e$  is the load factor of the evaporator. To this cost, the cost of an antifoam materials and calcium, to prevent corrosion, must be added. The cost of antifoam chemicals and calcium is

$$C_M (\$/\text{yr}) = 1720 W_p$$

where  $W_p$  is fresh water output, Mgd.

Operating costs of industrial complex were developed as the sum of the costs of raw materials, utilities, operating and maintenance, labor, overhead, interest costs (including return on investment and interest on working capital), etc. All industrial plants were assumed to have a 15-year life. The costs of raw materials used in industrial complex are listed in Table 6. II.

Operating costs of farm were taken as sum of the direct costs

---

\*This relationship is only for reactor with thermal power from 4600 to 10,000 Mw.

Table 6. II. Costs of the raw materials and wholesale price of products

Raw material	Cost \$/ton	Product	Wholesale price \$/ton
Bauxite	5.5	Aluminum	800.0
Coke	17.0	Ammonia	47.7
Phosphate rock	19.0	Ammonium nitrate	54.7
Salt	3.0	Caustic (NaOH)	80.0
Silica	1.0	Chlorine	- <sup>a</sup>
		Nitric phosphate	80.0
		Phosphorus ( $P_2O_5$ )	120.0
		Solar salt	4.0
		Urea	75.0

<sup>a</sup>Chlorine does not have any value in Iran. It's price, therefore, is assumed to be zero.

(seed, labor, marketing, etc.), excluding the costs of the water, power and fertilizer, and indirect costs (overhead, insurance, interest). Concerning the related costs such as water loss, management, interest on working capital and miscellaneous, the indirect annual cost was estimated to be about \$145 per year. Labor is charged 25¢/hr. Though this is greater than the present agricultural rate in Iran. However, as economic development takes place, wage rate naturally will rise. The operating costs were calculated by referring to Ref. 16b and 53 as base.

## C. Income

Credit for fossil material produced by the nuclear power source is calculated using the gross thermal power of the reactor. Credit assumed in this study is 0.0769 mills/kwhr (thermal).

Credit for electricity to grid is computed based on grid power in kilowatts electricity, operating hours per year, and the price of power at 3.4 mills/kwhr.

The costs of raw materials and the wholesale prices of industrial products used in the economic analysis of this complex are listed in Table 6. II. All the raw materials are assumed to be obtained locally except phosphate rock. Chlorine is assumed to have no value in Iran. It, however, could be utilized to treat the incoming seawater to prevent scaling.

The value of products is computed as the summation of annual production of the products times the sale prices listed in Table 6. II. for industry, and Table 6. III. for the farm. Ammonia will be bought and converted to ammonium nitrate, urea, and nitric phosphate, at the rate of 310 tons/day, for internal use.

The construction period is assumed to last 5 years and payment was distributed 7, 22, 42, 22, 7 percent at first, second, third, fourth, and fifth year respectively. With this schedule of construction payments, a factor,  $f$ , for including interest charges during construction was used where

$$f = 0.07 (1.06)^4 + 0.22 (1.06)^3 + 0.42 (1.06)^2 + 0.22 (1.06)^1 + 0.07 (1.06)^0 = 1.125$$

Table 6. III. Selected crops and their price

Crop	Price (\$/cwt)
Citrus	3.90
Cotton (lint (seed)	22.00
	3.12
Drybeans	7.80
Potatoes	1.82
Tomatoes	1.56
Wheat	3.47

Net annual benefit was obtained by deducting all expenses (operating costs and fixed charge at 8%) from the value of the products (gross sale).

Table 6. IV. shows the summary of the economic analysis of the complex.

Table 6. IV. Summary of economic analysis of the complex

Industrial power, Mw	1,021.00
Power for water, Mw	148.00
Grid power, Mw	31.00
Total electrical power, Mw	1,200.00
Desalted water, Mgd	500.00
Station size, Mw (thermal)	5,600.00
Farm size, acres	160,000.00
Number of reactors	2.00

Table 6. IV. (Continued)

---

Investment, millions of dollars	
Nuclear reactor island	112.00
Turbogenerator island	69.60
Evaporator plant	130.00
Seawater treatment plant	0.18
Industrial complex	363.00
Farm	152.00
Harbor	24.00
Town	22.50
Grid-tie facility	2.57
Fuel inventory	35.40
Working capital	51.40
Subtotal	962.65
Interest during construction	120.35
Total	1,083.00
Fixed charge, millions of dollars	
	86.60
Annual operating costs, millions of dollars	
Nuclear island <sup>a</sup>	2.20
Fuel cycle	19.20
Turbine generator island	0.70
Evaporator plant	2.60

---

<sup>a</sup>Insurance is included.

Table 6. IV. (Continued)

Industrial complex <sup>b</sup>	100.70
Farm <sup>b</sup>	28.80
Total	154.20
Value of Products (income), millions of dollars per year	
Credit for fissile material	3.45
Electricity to grid (3.4 mills/kwhr)	0.59
Industrial products	261.00
Farm products	93.50
Total	358.54
Net annual benefit, millions of dollars	117.70
Internal rate of return, %	16.90

<sup>b</sup>The cost of water and power is excluded.

## VII. CONCLUSION

Referring to the result of the economic analysis, Table 6. IV., one can conclude that even on a strictly monetary basis an agro-industrial complex is attractive. The use of advanced evaporator technology is one of the most important factors in economic viability of the complex.

It should be stated that small changes in basic water-yield relationship, crop prices, irrigation requirement, more high value crops, and increasing the capacity of the complex could rise significantly the internal rate of return. The change of evaporator from VTE to MSF, however, would decrease the internal rate of return of the complex by 2 points. The effect of excluding aluminum plant would be to decrease the rate of return quite significantly.

The author would like to emphasize the fact that if the complex could be undertaken by both Iran and Pakistan who already have some form of economic cooperation, the size of the complex could be larger, for example, 1000-Mgd water; thus there would be much higher and more attractive return. Since increasing the size of the complex improves the rate of return.

The agro-industrial complex appears capable of opening up a new avenue for economic growth of Iran with attractive natural deposits and land but devoid of fresh water.

Comparing the result of this study with that for the U. S. conditions (50) shows that the capital investment and the income from the sales are higher in Iran. But the effect of higher income is more than that of higher investment on the profit. This is, because the differences

in value of products between the U. S. and Iran is greater than the capital cost.

The production of some inorganic chemicals from the brine effluent are possible. These products, however, must be competitively produced and must be marketable. Market considerations is the most important factor in determining what products could be produced. Because of lack of information about the prices, need, and market conditions, the chemical products from the effluent brine was not considered in this study. It is clear, however, under favorable market conditions, modest increase in the profit of the complex is possible by production of such chemicals.



## VIII. SUGGESTION FOR FURTHER INVESTIGATIONS

The solution to the water shortage problem of the South coast of Iran, or better to say, the Gulf of Oman coast region which includes Mokran coast of Iran and Pakistan, should be sought in a series of logical steps. Development of a overall plant usually requires the establishment of an agency such as Oman coast Water Plant or Authority. This agency must be composed of a administrative board and a study group.

The logical steps for solution of water problem in Oman coast region could be organized as follows:

Step 1. The preliminary feasibility study to evaluate the various alternative solutions to the problem and identify the most promising solution(s) for further study.

Step 2. Economic feasibility analysis to evaluate the most promising solution sought.

Step 3. In this step many specific factors must be determined or surveyed. Examples of these are:

- a) Detailed political and social analysis,
- b) Market survey for the type and amount of products which the market could be expected to absorb.
- c) The likely location(s) for the complex and the smaller dispersed plants.
- d) The utilization survey of marine resources and its effect on the profit of the complex.
- e) The modes and costs for transportation of raw materials and

final products.

Step 4. The detailed engineering feasibility and economic study. The result of this step could serve as for a commitment for the design (or selection) of a desalination facility, energy source, and selection of the industrial and agricultural products.

Step 5. Preparation of economic and technical soundness analysis.

Step 6. Construction of the complex based on economic and technical soundness analysis.

The first two steps have been taken in this study. Action for the Steps 3, 4, 5, and 6, which could only be accomplished in Iran, are left for further investigations.

## IX. REFERENCES

1. Amouzegar, K. Some statistical data about sources of water supply systems in Iran. International Conference on Water for Peace. Vol. 8. Pp. 821-827. Washington, D.C., U.S. Government Printing Office. 1967.
2. Baron, S. Economics of reactors for power and desalination. In Levine, S. N. Selected papers on desalination and ocean technology. Pp. 168-172. New York, N.Y., Dover Publications, Inc. 1968.
3. Bayani, A. G. The general policy of the Iranian Ministry of Water and Power in development of water resources. In International Conference on Water for Peace. Vol. 2. Pp. 329-346. Washington, D.C., U.S. Government Printing Office. 1967.
4. Bechtel Corporation. Engineering and economic feasibility study for combination nuclear power and desalting plant: Summary. San Francisco, Calif., Metropolitan Water District of Southern California, U.S. Department of Interior, and U.S. Atomic Energy Commission. Dec. 1965.
5. Blanco, R. E., W. C. Yee, W. E. Clark, J. M. Holmes, and R. Salmon. A close-cycle process for preventing scale formation in evaporators and producing industrial chemicals at a nuclear desalination plant. U.S. Atomic Energy Commission Report ORNL-4057 (Oak Ridge National Lab., Tenn.). Sept. 1967.
6. Blanco, R. E., J. M. Holmes, R. Salmon, and J. W. Ullmann. An economic study of the production of ammonia using electricity from nuclear desalination reactor complex. U.S. Atomic Energy Commission Report ORNL-3882 (Oak Ridge National Lab., Tenn.). June 1966.
7. Brice, D. B. and D. A. Yashin. Selection of nuclear reactors for desalination. In International Conference on Water for Peace. Vol. 2. Pp. 25-36. Washington, D.C., U.S. Government Printing Office. May 1967.
8. Catalytic Construction Company. A study of desalting plants (15 to 150 Mgd) and nuclear power plants (200 to 1500 Mwth.) for combined water and power production. U.S. Atomic Energy Commission Report No. NYO-3316-1 (New York Operations Office, AEC). Sept. 1964.
9. Decker, G. L., W. B. Wilson, and W. B. Bigg. Nuclear energy for industrial heat and power. Chemical Engineering Progress 64: 3. March 1968.

10. D'orival, M. Caractéristiques des installations mixtes produisant de l'eau dessalée et de l'électricité à partir d' une même source d'énergie thermiques. Desalination, The International Journal on the Science and Technology of Water Desalting 4, No. 1: 66-79. 1968.
11. Edison Electric Institute. Survey of current economics of natural and desalted water in the United States. Edison Electric Institute (New York, N.Y.) Research Project RP-67. 1965.
12. Fruth, Hans. Cost determination and comparison of nuclear and fossil fueled dual-purpose power and desalination plant. First International Symposium on Water Desalination Proceedings 3: 753-765. Oct. 1965.
13. General Electric Company. Price Handbook. Section 8802: 10. Sunnyvale, Calif., G. E. Company. August 22, 1966.
14. Geoller, H. E. Tables for computing manufacturing costs of industrial products in an agro-industrial complex. U.S. Atomic Energy Commission Report ORNL-4296 (Oak Ridge National Lab., Tenn.). 1968.
15. Glasston, S. and A. Sesonsky. Nuclear reactor engineering. 2nd ed. Princeton, New Jersey, D. Van Nostrand Company, Inc. c1963.
- 16a. Great Britain Meteorological Office. Weather in the Indian Ocean. Vol. 1. London, H.M.S. Stationary Office, author. 1943.
- 16b. Guide line to production costs and practices: Imperial County Crops. California (El Centro) Agricultural Extension Services Circulation No. 104. (No date.)
- 17a. Hainsworth, W. R., D. B. Brice, and M. R. Dusabek. The role of nuclear energy in water conversion by distillation. Saline Water Conversion Symposium Proceedings. May 1957: 398-407. 1958.
- 17b. Hammond, R. P. Desalted water for agriculture. In International Conference on Water for Peace. Vol. 2. Pp. 184-197. Washington, D.C., U.S. Government Printing Office. May 1967.
18. Holton, H. T. and L. S. Galstaun. Study of 150 MGD desalted water-power dual plant for Southern California. First International Symposium on Water Desalination Proceedings 3: 543-555. Oct. 1965.
19. International Atomic Energy Agency. Costing methods for nuclear desalination. International Atomic Energy Agency Technical Report Series No. 69, Vienna, Austria. 1966.

20. International Atomic Energy Agency. Desalination of water using conventional and nuclear energy. International Atomic Energy Agency Technical Report Series 24, Vienna, Austria. 1964.
21. International Atomic Energy Agency. Introduction to the methods of estimating nuclear power generating costs. International Atomic Energy Agency Technical Report Series No. 5, Vienna, Austria. 1961.
22. Iran Ministry of Water and Power. Survey of possibility of the use of nuclear energy for power in Iran. Tehran, Iran, Ministry of Water and Power. Sept. 1968.
23. Kramer, A. W. Boiling water reactors. Reading, Massachusetts, Addison-Wesley Publishing Company, Inc. 1958.
24. Lane, J. A. Economics of nuclear power. Nuclear Science Annual Review 16: 345-378. 1966.
25. Light Water Reactor Task Force. Current status and future technical and economic potential of light water reactors. U.S. Atomic Energy Commission Report WASH-1082 (Atomic Energy Commission, Washington, D.C.). March 1968.
26. Lockhart, R. W. Feasibility study of boiling water reactor nuclear steam supply system with capacity up to 10,000 Mwth. U.S. Atomic Energy Commission Report GEGR-5155 (General Electric Co., Sunnyvale, Calif., Advanced Products Operation). February 1967.
27. Loginov, A. A., Y. I. Koryakin, V. A. Chernyaev, I. I. Zakharov, B. A. Stoyashchev, and A. D. Suponev. Analysis of the technical and economic indicators of nuclear power desalination plants. First International Symposium on Water Desalination Proceedings 3: 345-359. Oct. 1965.
28. Ma, Benjamin M. Nuclear reactors for seawater desalination. Ames, Iowa, Dept. of Nuclear Engineering, Iowa State University. 1966.
29. Mahdavi, H. Summary of water resources development in Iran. In International Conference on Water for Peace. Vol. 6. Pp. 68-73. Washington, D.C., U.S. Government Printing Office. 1967.
30. McGill, I. T. Map of the coastal land forms of the world. Geographical Review 48, No. 3: 402-405. 1958.
31. Meigs, P. Coastal desert, prime customers of desalination. First International Symposium on Water Desalination Proceedings 3: 721-730. 1965.

32. Nelson, A. G. Costs and returns for major field crops in central Arizona. Arizona Agricultural Extension Service Technical Bulletin 174. August 1965.
33. Popkin, Roy. Desalination, water for the world future. New York, N.Y., Frederick A. Praeger, Publishers. 1968.
34. Post, R. G. and Robert L. Seale. Water production using nuclear energy. Tucson, Arizona, The University of Arizona Press. 1966.
35. Ramey, J. T., J. A. Swartout, and W. A. Williams, Jr. Nuclear energy-potential for desalting. First International Symposium on Water Desalination Proceedings 1: 561-573. Oct. 1965.
36. Reul, R. I. Which investment appraisal technique should you use. Chemical Engineering 9: 212-218. 1968.
37. Revelle, R. Water and land. In The World Food Problem. Vol. 2. Pp. 407-469. Washington, D.C., The White House. 1967.
38. Rouhani, M. Policies regarding water resources development in Iran. In International Conference on Water for Peace. Vol. 5. Pp. 44-50. Washington, D.C., U.S. Government Printing Office. May 1967.
39. Sindt, H. A., I. Spiewak, and T. D. Anderson. Cost of the power from nuclear desalting plant. Chemical Engineering Progress 63, No. 4: 41-45. 1967.
40. Spiegler, K. S. Principles of desalination. New York, N.Y., Academic Press. 1966.
41. Spiewak, I. A large desalination reactor based on current technology. Nucleonics 21: 7. July 1963.
42. Spiewak, I. and J. K. Franzreb. Flexibility in production of power and water from nuclear desalination plants. U.S. Atomic Energy Commission Report ORNL-TM-1564 (Oak Ridge National Lab., Tenn.). Sept. 1966.
43. Squires, A. M. Steelmaking in an agro-industrial complex. U.S. Atomic Energy Commission Report ORNL-4294 (Oak Ridge National Lab., Tenn.). 1968.
44. Stout, P. R. Potential agricultural production from nuclear-powered agro-industrial complexes designed for the upper Indo-Gangetic Plain. U.S. Atomic Energy Commission Report ORNL-4292 (Oak Ridge National Lab., Tenn.). 1968.

45. Sun, R. C. Extrapolation of cost data from the industrialized to developing countries. Manila, Philippines, Manila Electric Company. (No date.)
46. Tennessee Valley Authority. Comparison of coal-fired and nuclear power plants for TVA system. Chattanooga, Tennessee, Tennessee Valley Authority. June 1966.
47. U.S. Dept. of Interior. Office of Saline Water. Conceptual design study of a 250 MGD combined vertical tube-flash evaporator desalination plant. U.S. Department of Interior, Office of Saline Water Report 391. August 1968.
48. U.S. Dept. of Interior. Office of Saline Water. Conceptual design of a 250 MGD multistage flash desalination plant. U.S. Department of Interior, Office of Saline Water Report 214. Sept. 1966.
49. U.S. Dept. of Interior. Office of Saline Water. A standardized procedure for estimating costs of saline water conversion. U.S. Department of Interior, Office of Saline Water Report PB-161375. March 1965.
50. U.S. Oak Ridge National Laboratory. Nuclear energy center: Industrial and agro-industrial complexes. U.S. Atomic Energy Commission Report ORNL-4290 (Oak Ridge National Lab., Tenn.). November 1968.
51. U.S. Office of Science and Technology. Appendices to an assessment of large power seawater desalination plants. Interagency Task Force, U.S. Office of Science and Technology. March 1964.
52. U.S. Office of Science and Technology. An assessment of large nuclear powered seawater desalination plants. (A report of an Interagency Task Group, submitted to the President's Office of Science and Technology.) Washington, D.C., U.S. Government Printing Office. March 1964.
53. Van Arsdall, R. N. Labor requirements, machinery, investments and annual costs for the production of selected field crops in Illinois. Illinois Agricultural Extension Service Report AE 4112. 1965.
54. Wilson, J. R. and E. A. Cadwallder. Guidelines for determining feasibility of desalination. In International Conference on Water for Peace. Vol. 2. Pp. 329-346. Washington, D.C., U.S. Government Printing Office. May 1967.
55. Yaron, D. The demand for water. Jerusalem, Israel Agriculture Department, Hebrew University. 1959.

## X. ACKNOWLEDGMENTS

This study originated in a suggestion made by Dr. Glenn Murphy, Distinguished Professor, Head of Department of Nuclear Engineering.

The author takes great pleasure in expressing his appreciation to Dr. Glenn Murphy for his help, advice, and encouragement throughout the study.

Gratitude is also expressed to Dr. Benjamin M. Ma of the Department of Nuclear Engineering for his help and useful suggestions.

The author is very grateful to Mr. K. Ferdows of the Plan Organization, Mr. N. Movahed of the Ministry of Water and Power, and Mr. N. Nowbahar and Mr. V. Isakhanian of the Ministry of Economy, Tehran, Iran, for the useful information and data used in this study.